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THE EFFECT OF COOLING-AIR BLOWERS ON THRUST POWER

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CONTENTS

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THE EFFECT OF COOLING-AIR BLOWERS ON THRUST POWER

By Carl B. Palmer and Maurice J. Brevoort

SUMMARY

An assumed airplane was used to illustrate the analysis of the effect of cooling-air blowers on thrust power. The performance and engine characteristics selected for the airplane are essentially those of a modern pursuit airplane. The results obtained apply in particular to the assumed airplane, but the conclusions have a general application.

When aviation-engine heat exchangers are used above their design altitude, blowers may be used to give additional available pressure and to increase the jet thrust, although the amount of blower power that may profitably be used is definitely fixed by the operating conditions. When the heat exchanger is large enough that a blower gives no thrust increase, the net thrust from the engine and cooling system is higher than can be obtained from any combination of blower and smaller heat exchanger.

INTRODUCTION

When an aircraft-engine heat exchanger is to be used above its design altitude, some auxiliary equipment may be required to give proper cooling and to keep the cooling cost from becoming exorbitant. The decrease in air density with altitude makes it difficult or impossible to obtain a weight rate of flow of air sufficient for proper cooling. To alleviate this difficulty, more pressure drop must be made available across the heat exchanger or the exchanger must be redesigned to allow the proper cooling-air flow with the low pressure drop available.

Axial fans, or blowers, have been used in front of air-cooled engines not only to increase the pressure available for cooling but also to increase the jet thrust from the cooling air. When air is compressed, heated, and then allowed to escape to the atmosphere through a suitable duct, a thrust is obtained (the "Meredith effect") that, with sufficient heating and compression, is of considerable magnitude. Although an increase in the blower power increases this jet thrust, it also decreases the power that can be used for the propeller. Obviously the best blower is the one giving the highest net thrust while properly cooling the engine.

Because it is impossible to set down a simple relation between the operational parameters and the blower power resulting in maximum net thrust, and because there is much interest in such a relationship, the present report has been prepared to show how the net thrust power from a typical air-cooled engine varies with the power used in a blower. For simplicity, the calculations assume an infinite number of possible blowers in order to have the defined efficiency under all conditions. The range of conditions covered is from sea level to an altitude of 40,000 feet, for three fin widths, and at high speed and two climbing speeds. The conclusions apply as well to liquid-cooled engines, and the method of calculation is applicable to any type of cooling system with arbitrary variations in propeller and blower efficiencies.

Acknowledgment is made to Mr. U. T. Joyner of the NACA Physical Research Division for preparation of the Mollier chart used in this analysis.

METHOD

The following method has been followed in making the analysis of the effect of cooling-air blowers on thrust power. The power to operate the blower, at 70-percent-adiabatic and 95-percent-shaft efficiencies, is subtracted from the normal engine power, and the remaining engine power is put into a propeller operating at 80-percent efficiency. The algebraic sum of the jet and the propeller thrust powers is defined as the net thrust power within the compass of this report.

The calculations are made for an air-cooled engine with a normal power rating of 1675 horsepower. This engine is installed in an airplane with a gross weight of 12,000 pounds and dissipates 445 Btu per second through 1.0-inch aluminum fins. The weight rate of cooling-air flow is taken directly or calculated from reference 1.

The main paper contains a summary of the most pertinent results, and a detailed discussion of the results, illustrated with graphs, is given as appendix B. (The symbols used throughout the paper are defined in appendix A.) The method for calculating the jet thrust power and the blower power cost are given in appendix C, and a discussion of the conditions and assumptions upon which these calculations are based is given in appendix D along with an evaluation of the degree of approximation involved in each assumption.

RESULTS

The five major variables considered herein are: net thrust power, blower power, airplane speed, altitude, and fin width. Since the cooling is adequate and the heat to be dissipated is constant, the most important problem is to make the net thrust power maximum. Because this report is primarily a blower analysis, the effects of airplane speed, altitude, and fin width are shown by curves plotted on coordinates of thrust power and blower power. Other curves show the effect of blower power on the thermodynamic efficiency of the cooling-air heat cycle. A representative cycle is also given.

Airplane Speed

At altitudes where much of the pressure drop available is needed for cooling, the blower power giving maximum thrust increases as the airplane speed decreases. (See fig. 1.) In climb the airplane speed is decreased, pressure available from ram falls off and, aside from all considerations of thrust, a blower may be necessary to provide adequate pressure for properly cooling the engine. For high-speed flight at 40,000 feet the maximum thrust is obtained with about 200 horsepower for the blower. As the speed falls below 300 miles per hour, more than 300 horsepower is needed in the blower to get maximum thrust and the engine fails to cool with less than 160 blower horsepower. (Note that these values are only for 1.0-in. fins.) When the altitude is low enough that cooling is no problem, even at low speed and with no blower, this velocity effect

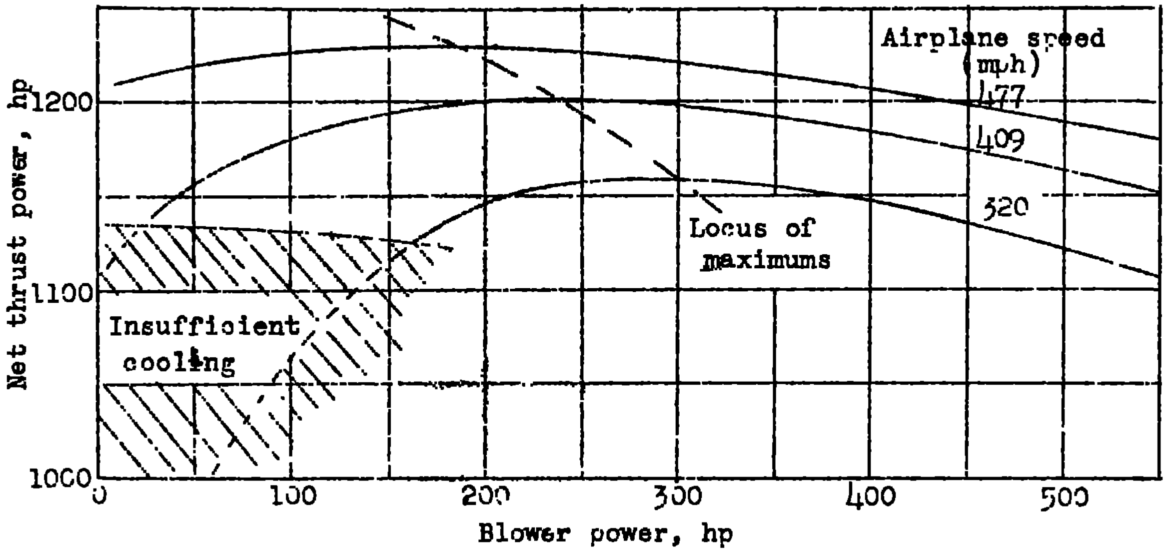

Figure 1.- Effect of airplane speed on the variation of net thrust power with blower power at an altitude of 40,000 feet.

is reversed. Figure 2, which shows the effect of airplane speed at sea level, illustrates this change.

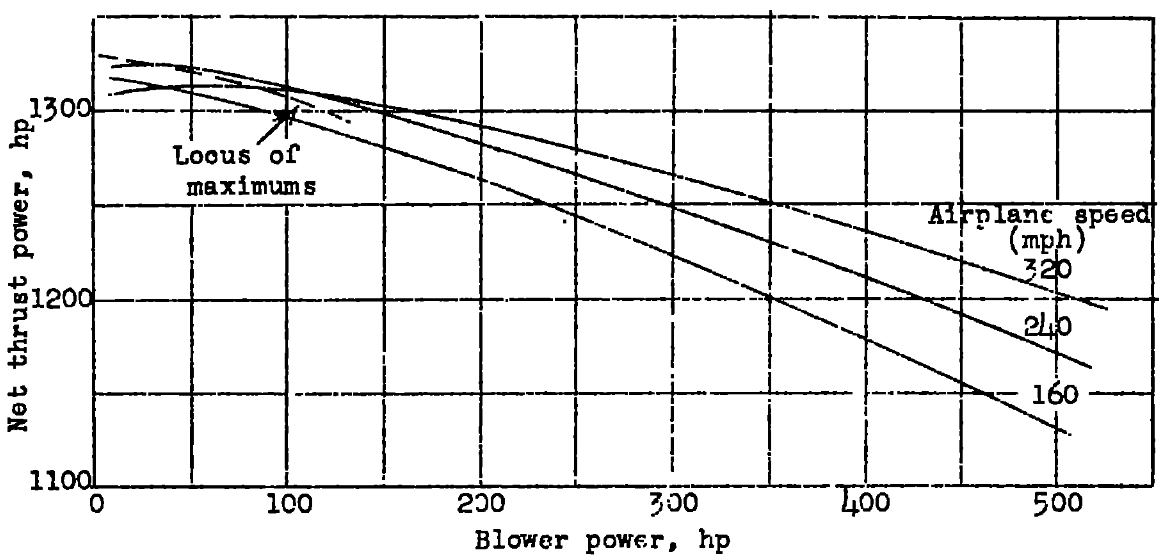

Figure 2.- Effect of airplane speed on the variation of net thrust power with blower power at sea level.

Altitude

For a particular flight condition - for example, maximum lift-drag ratio, level flight, etc. - an increase in altitude increases the optimum blower power. (See fig. 3.)

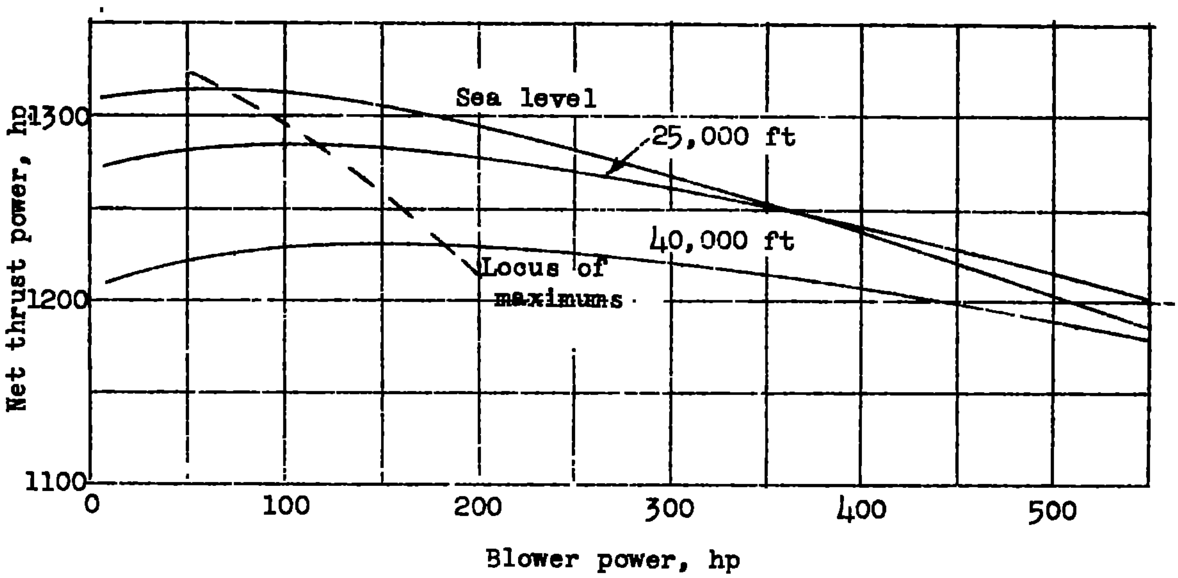

Figure 3.- Effect of altitude on the variation of net thrust power with blower power at high speed.

For high-speed flight this engine, which requires only about 70 horsepower for the blower in order to get maximum thrust at sea level, requires nearly 180 blower horsepower for maximum thrust at 40,000 feet. In the climb condition (see fig. 4) the optimum blower power increases even more rapidly with altitude.

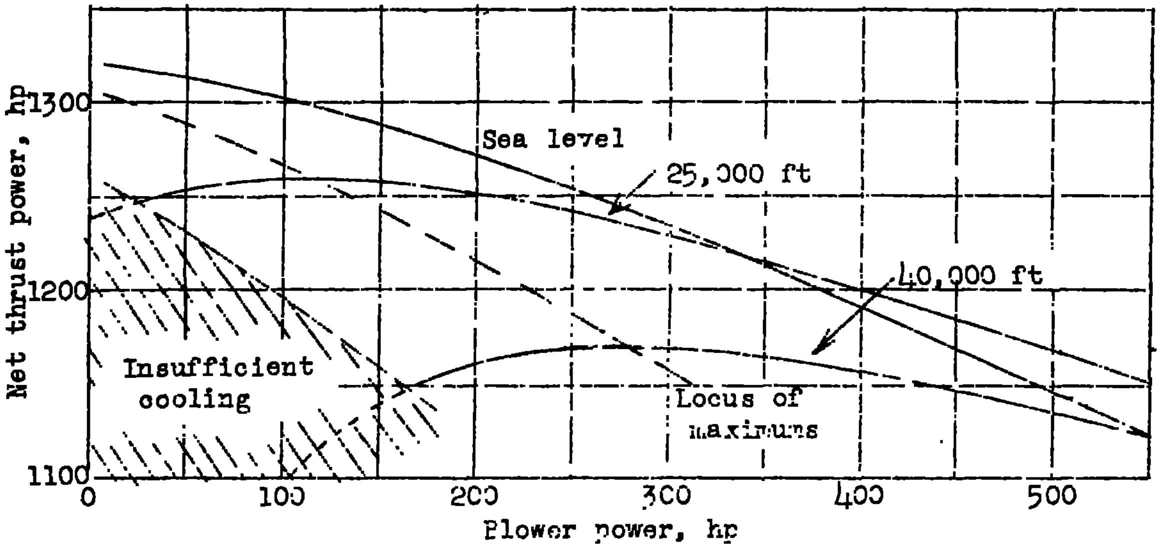

Figure 4.- Effect of altitude on the variation of net thrust power with blower power at the maximum lift-drag ratio L/D.

Fin Width

Widening the fins has been suggested (reference 1) as a means of improving the cooling characteristics. Figure 5 shows the effect of fin width upon the net

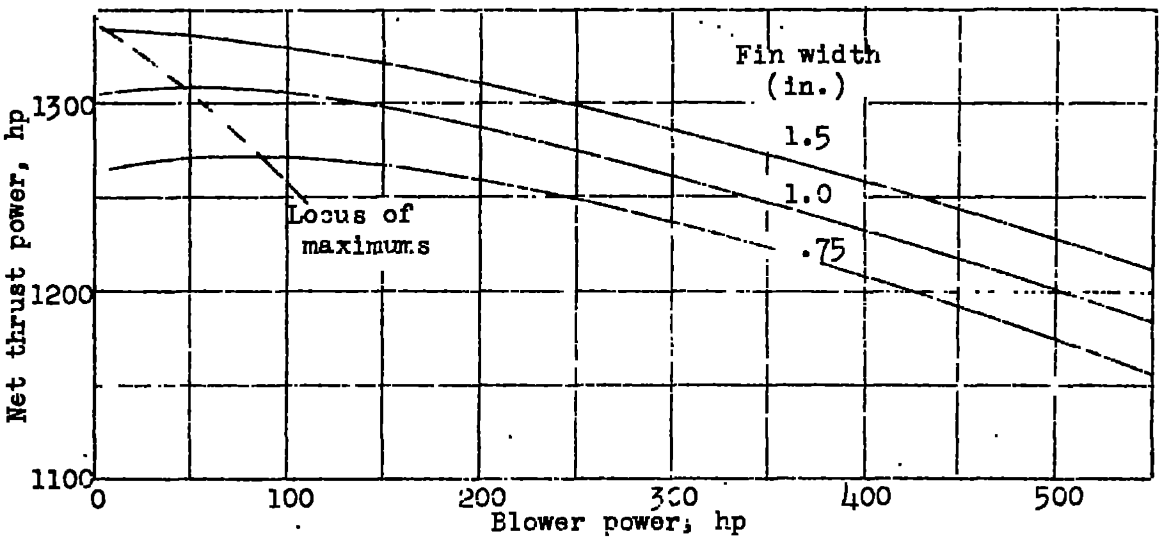

Figure 5.- Effect of fin width on the variation of net thrust power with blower power for high speed at sea level.

thrust and the permissible blower power for high speed at sea level. Increasing the fin width from 0.75 inch to 1.5 inches decreases the optimum blower power from 80 horsepower to zero and increases the maximum net thrust power from 1275 to 1340 horsepower. Starting from zero blower power with 1.0-inch fins, the addition of a 50-horsepower blower gives a 5-horsepower thrust increase. If, instead of the blower, another 1/2 inch of fin width is added, the increase in thrust power is more than 35 horsepower.

At high altitudes the effect of fin width is even more pronounced. At an altitude of 40,000 feet a 150-horsepower blower gives a 25-horsepower thrust increase, while an extra 1/2 inch of fin width adds 125 thrust horsepower. (See fig. 6.) This information is presented in the form of contours of constant

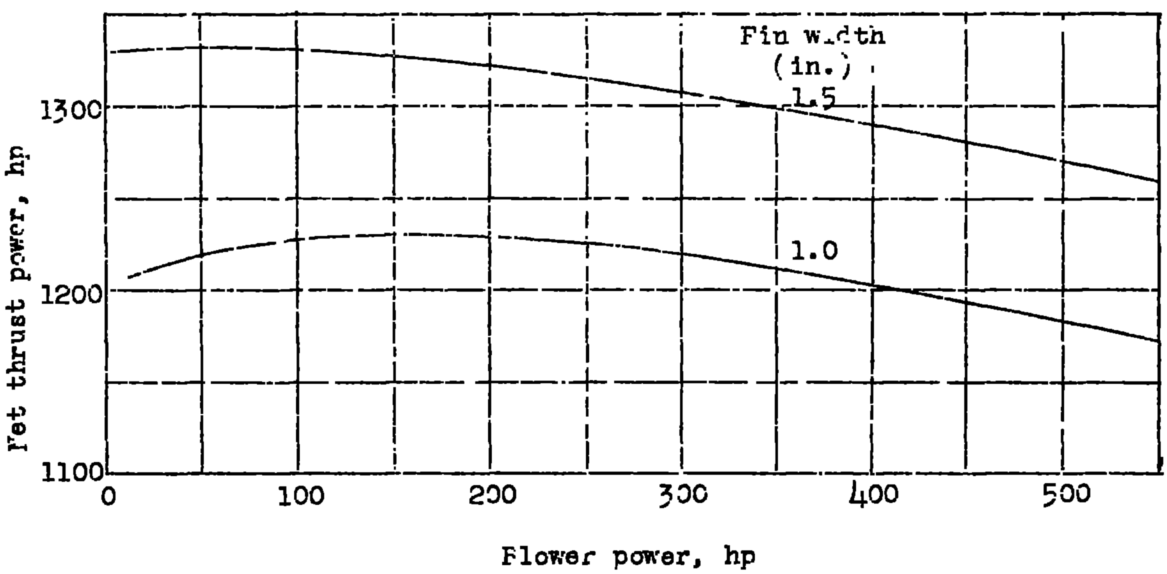

Figure 6.- Effect of fin width on the variation of net thrust power with blower power for high speed at an altitude of 40,000 feet.

thrust power plotted on coordinates of fin width and blower power in figure 7. It is obvious from figure 7 that the maximum net thrust occurs with relatively wide fins and low blower powers.

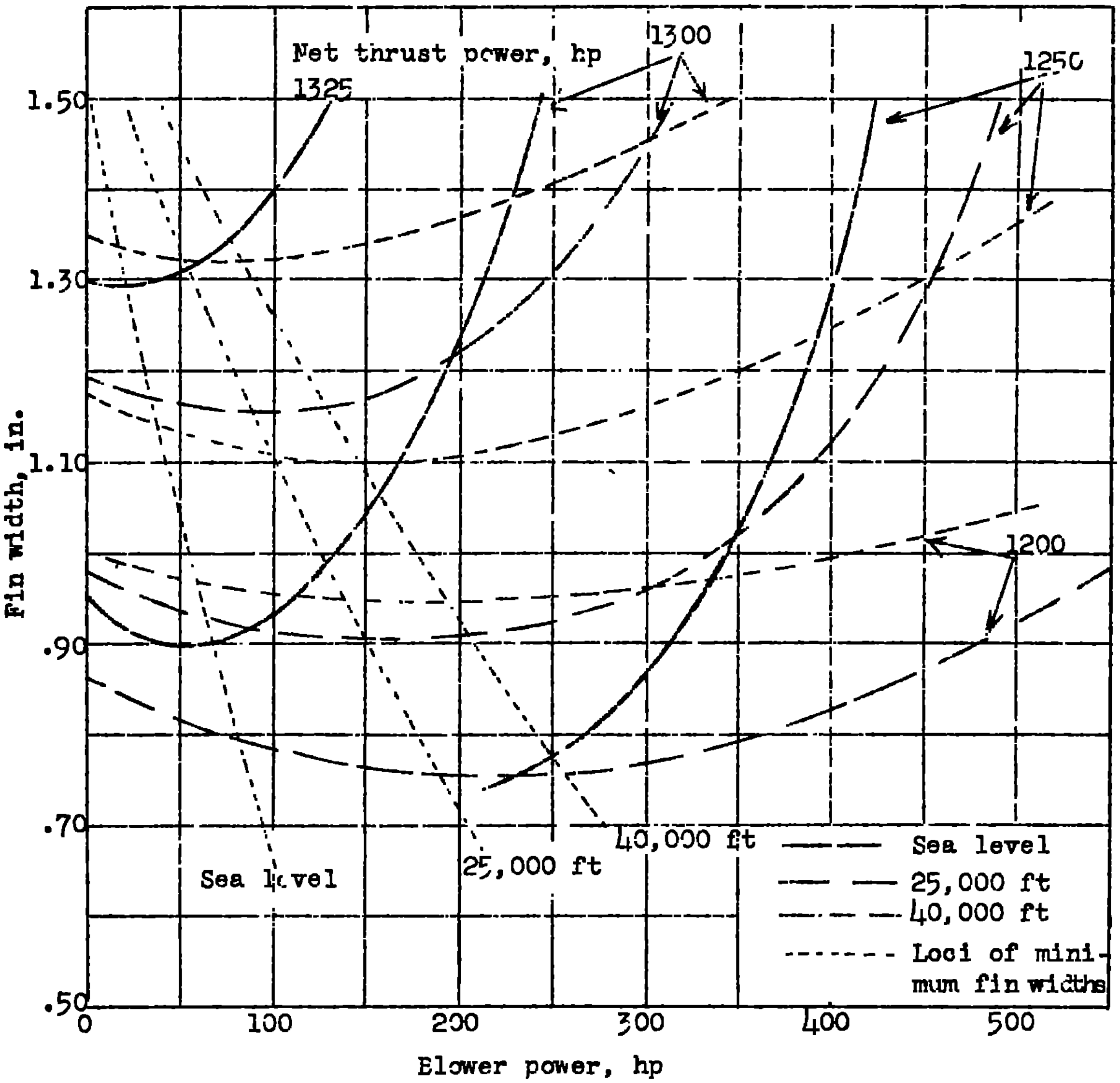

Figure 7.- Net thrust power as a function of fin width and blower power at high speed.

Physical Significance of Heat Cycle

In figure 8 a representative cooling-air heat cycle for high blower compression is shown with notations explaining the significance of various points and distances on the cycle. All energies are read on the enthalpy h scale, and the velocity can be determined directly from the kinetic energy. Point 0 is the free-stream state point for the cooling air. The ram kinetic energy raises the temperature and pressure to that at point B. The energy added by the blower increases the entropy as well as the temperature and pressure to that at point 1. (The dashed line indicates that the state path cannot be defined.) As the air accelerates into the fins, its kinetic energy increases to that at point 2. In passing through the hot fins, the temperature and the kinetic energy increase and the pressure falls off somewhat as shown by point 3. The line between points 3 and 4 describes the air as it is dumped behind the fins. Kinetic energy is lost with only a little pressure recovery, and the entropy increases again. Between points 4 and 5 the air accelerates to the cowling exit where it exhausts at free-stream static pressure p_o. A comparison of the initial ram kinetic energy and the kinetic energy at the cowling exit shows a velocity increase and therefore a positive jet thrust. A comparison, however, of exit kinetic energy and the total mechanical energy input (ram plus blower energies) shows a net loss in mechanical energy.

Thermodynamic Efficiency

The loss in mechanical energy mentioned in the preceding section is measured by the thermodynamic efficiency of the heat cycle. This efficiency is defined in reference 2 as the ratio

$$\frac{\text{Heat input - Heat rejected}}{\text{Heat input}}$$

When more heat is rejected than is put in, then of necessity mechanical energy equal to the difference is being

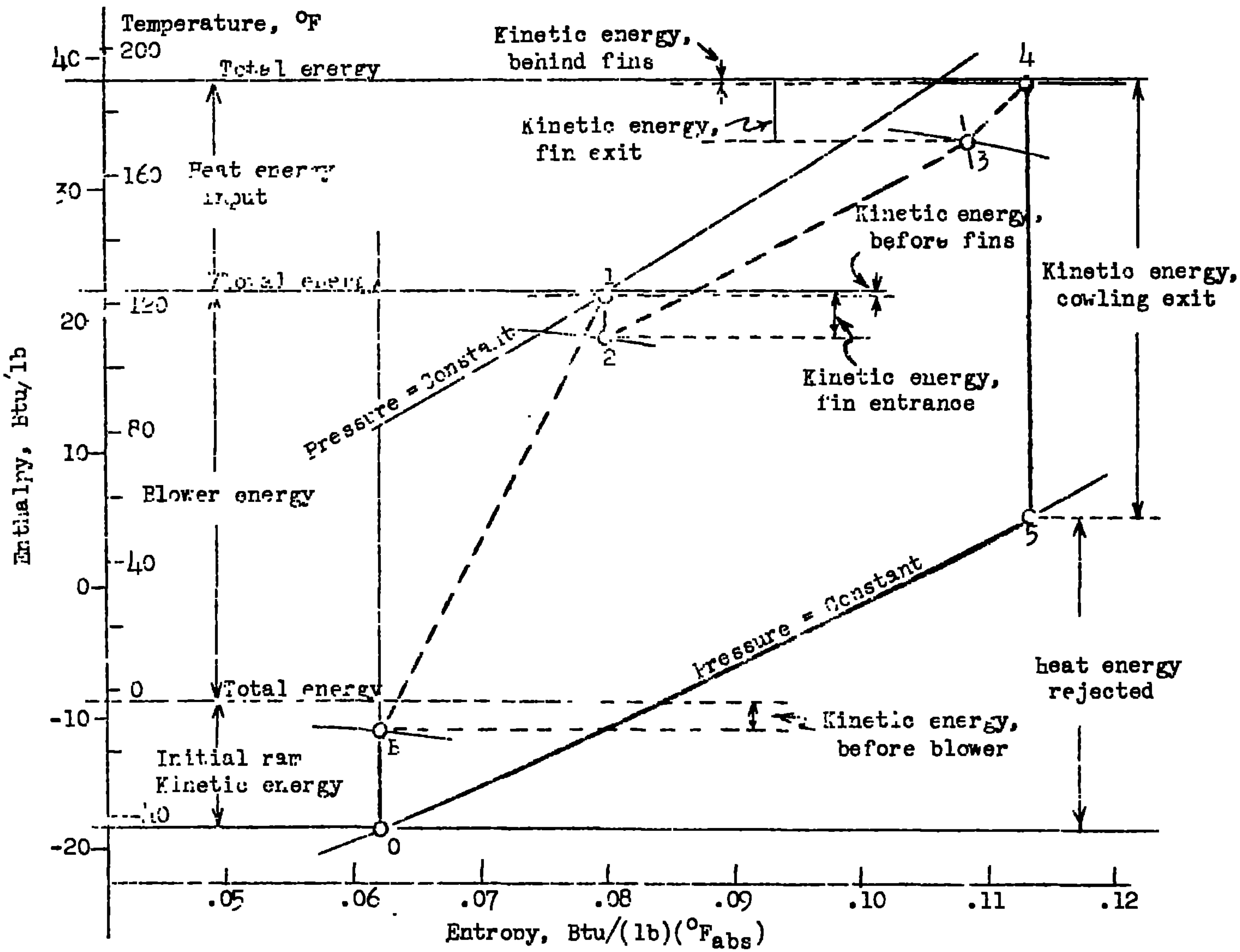

Figure 8.- Cooling-air heat cycle for high speed at 40,000 feet. Blower efficiency η_B, 70 percent; blower pressure rise Δp_B, 3.5 pounds per square inch.

dissipated as heat and the thermodynamic efficiency is negative. Figure 9 shows the efficiency of the cooling-air heat cycle for several fin widths and blower efficiencies. It is difficult to obtain a positive efficiency and even under ideal conditions the efficiency is quite small.

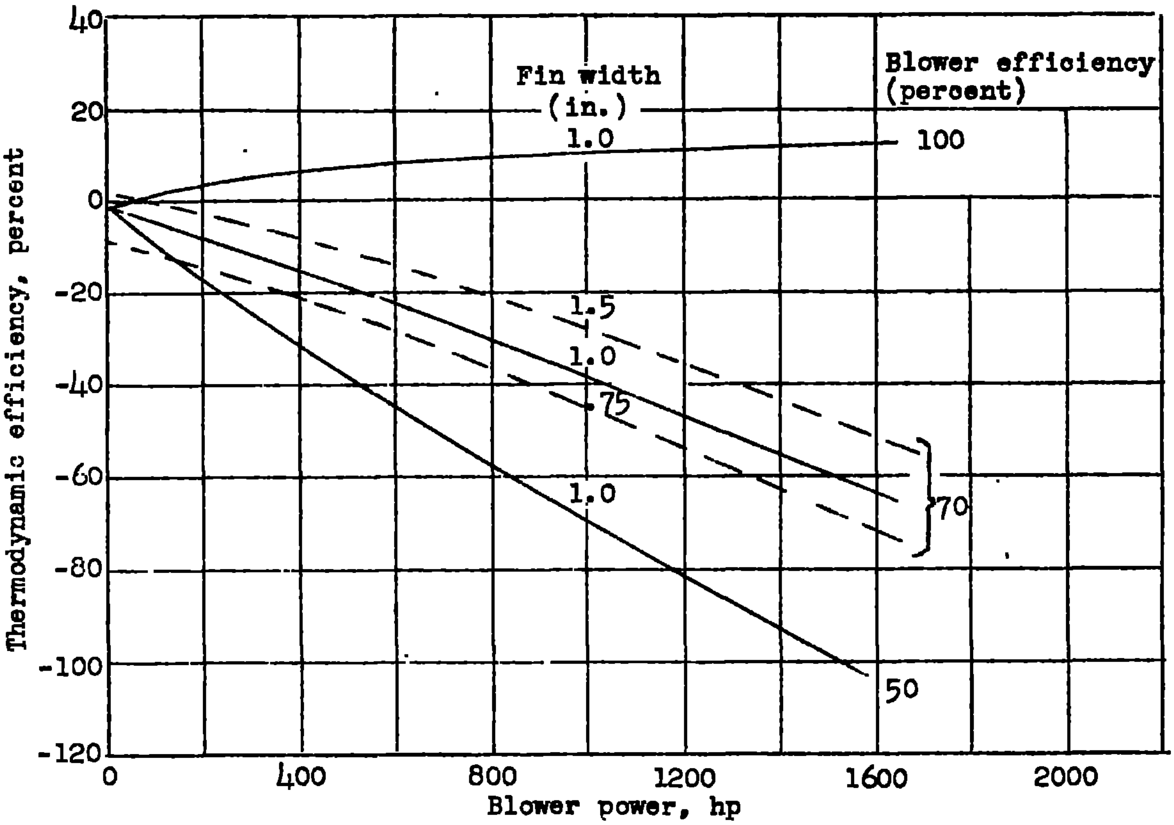

Figure 9.- Thermodynamic efficiency of the cooling-air heat cycle for high speed at sea level.

Even though the thermodynamic efficiency η_C is almost invariably negative and the assumed blower efficiency η_B in general is only 70 percent, the results show that some blower power in excess of that required for cooling is desirable. Thermodynamic and blower efficiencies are relatively unimportant compared with jet efficiency η_J.

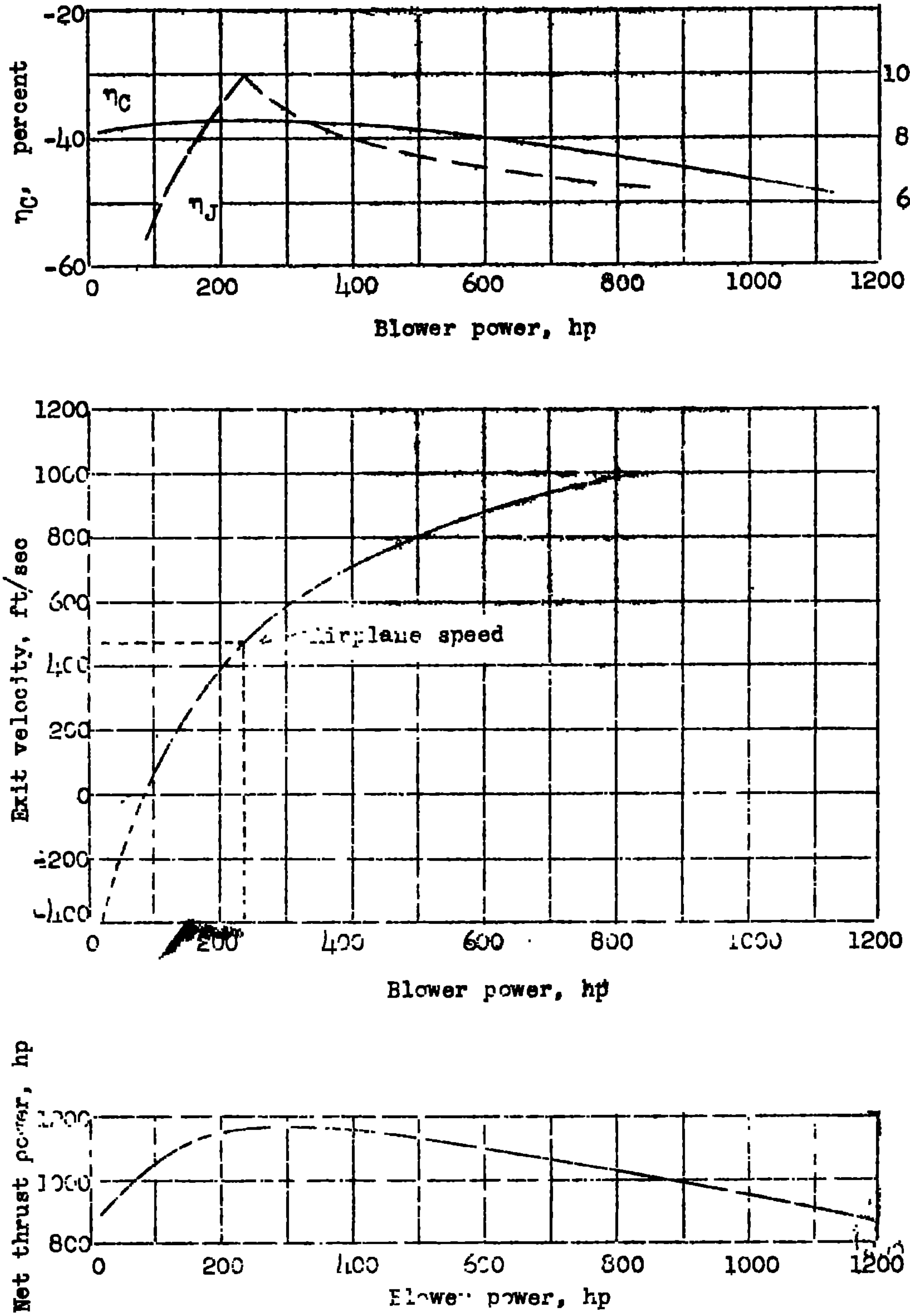

Figure 10.- Thermodynamic and jet efficiencies, exit velocity, and net thrust power as functions of blower power. Speed, 470 feet per second; altitude, 40,000 feet.

Jet efficiency so dominates the cooling situation that the optimum blower power, to a first approximation, is selected to make the exit velocity the same as the free-stream velocity. In this case the jet efficiency is 100 percent. (See fig. 10.) The addition of heat to the cooling air and changes in blower efficiency make only trivial changes in the optimum exit velocity.

An examination of the curves (fig. 10) taken from various figures throughout the report for the case of climb at 40,000 feet bears out the general statements just made. On the curve of exit velocity against blower power, the speed at which the exit velocity is the same as airplane speed is indicated. Comparison of the blower power which gives this exit velocity with the blower power giving the maximum net thrust power shows almost exact agreement.

CONCLUSIONS

The charts presented, which show the relations between the net thrust power and the power put into the blower, make evident several general rules. These rules are:

1. A blower may be used to increase the maximum altitude of operation for a particular heat-exchanger installation. The highest altitude at which proper cooling is possible, even with a blower, is definitely limited by the dimensions of the heat exchanger.

2. The jet efficiency so dominates the use of blower power that, to all practical purposes, the optimum blower power is that required to give an exit velocity equal to free-stream velocity. This velocity gives a jet efficiency of 100 percent.

3. In redesigning a heat exchanger for high altitude, sufficient cooling surface should be used to cool properly without a blower. When finning that gives the maximum net thrust with no blower is used, this thrust is substantially higher than can be obtained with any narrower fins and any amount of blower compression. When the use of a blower produces a greater thrust from the power plant, this increase is not so much a measure of the blower excellence as it is a measure of heat-exchanger inadequacy.

4. The efficiency of the cooling-air heat cycle is so low that under no conditions considered when the cooling is adequate does an increase in blower power cause an equal increase in net thrust power.

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APPENDIX A

SYMBOLS

A	cross-sectional area, sq ft
C_L	lift coefficient
D	drag force, lb
g	acceleration due to gravity, ft/sec^2
H	heat dissipation by exchanger, Btu/sec
h	enthalpy (heat content), Btu/lb
L	lift force, lb
P	power, hp
p	static pressure, lb/sq ft or lb/sq in.
T	temperature, $^{\circ}F$
V	velocity, fps
v	specific volume, cu ft/lb
W	weight rate of flow of air, lb/sec
η_B	adiabatic efficiency of blower-diffuser unit, ratio of isentropic to actual enthalpy increase for given static-pressure rise
η_C	thermodynamic efficiency of cooling-air heat cycle (reference 2) $\left(1 - \dfrac{T_4 - T_1}{T_5 - T_0}\right)$
η_J	jet efficiency, $\begin{cases} \dfrac{2V_0}{V_0 + V_5} & \text{for } V_5 > V_0 \\ \dfrac{V_0 + V_5}{2V_0} & \text{for } V_5 < V_0 \end{cases}$

η_p propeller efficiency, ratio of thrust power to power input

η_R efficiency of ram compression, ratio of actual to isentropic pressure rise for given total-energy increase

η_s blower shaft efficiency, ratio of power delivered to air to power taken from engine by blower

Subscripts:

0 free-stream conditions

B,1,2,3,4,5 conditions at corresponding station in cowling

APPENDIX B

RESULTS IN DETAIL

The results presented in this section were summarized in the main paper. Here they are given in detail and for a much wider range than would be practicable in any aircraft installation.

Figures 11, 12, and 13 give the thrust power as it varies with the blower power at sea level, 25,000 feet, and 40,000 feet, respectively. On each graph the propeller and jet thrust powers, which are added algebraically to give the net thrust power, are shown for three airplane speeds. The speeds shown on the graphs were selected to cover the range of flight operation from above level-flight high speed to speeds below that for maximum L/D.

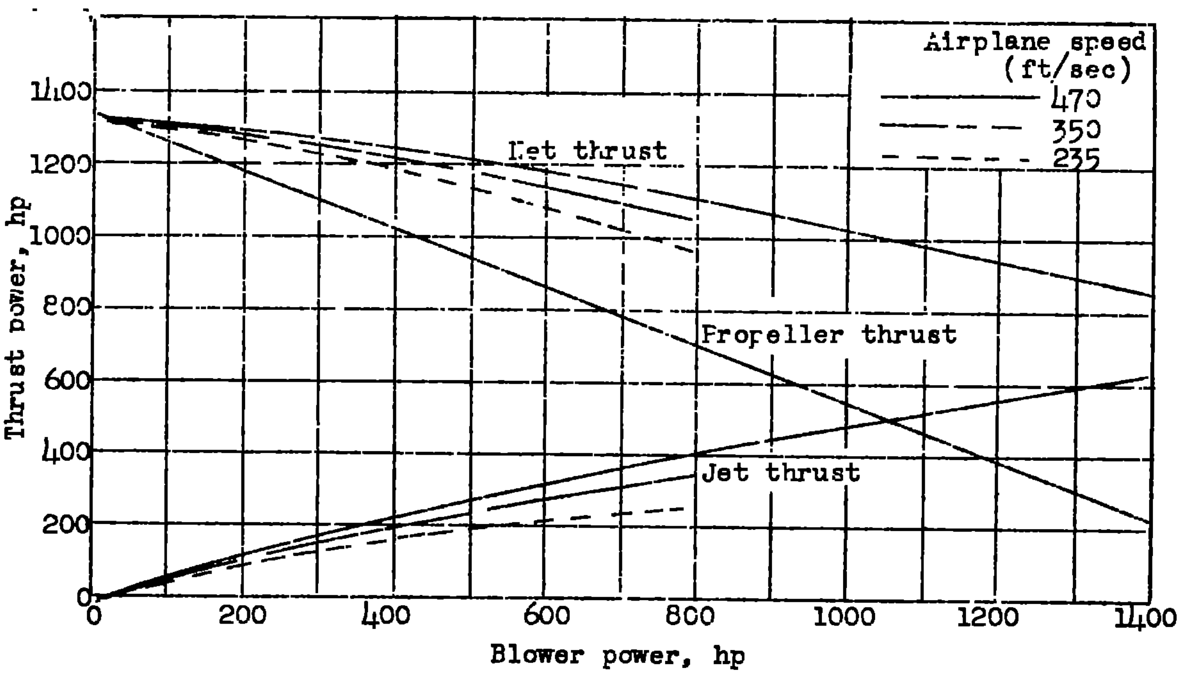


Figure 11.- Thrust as a function of speed and blower power at sea level.

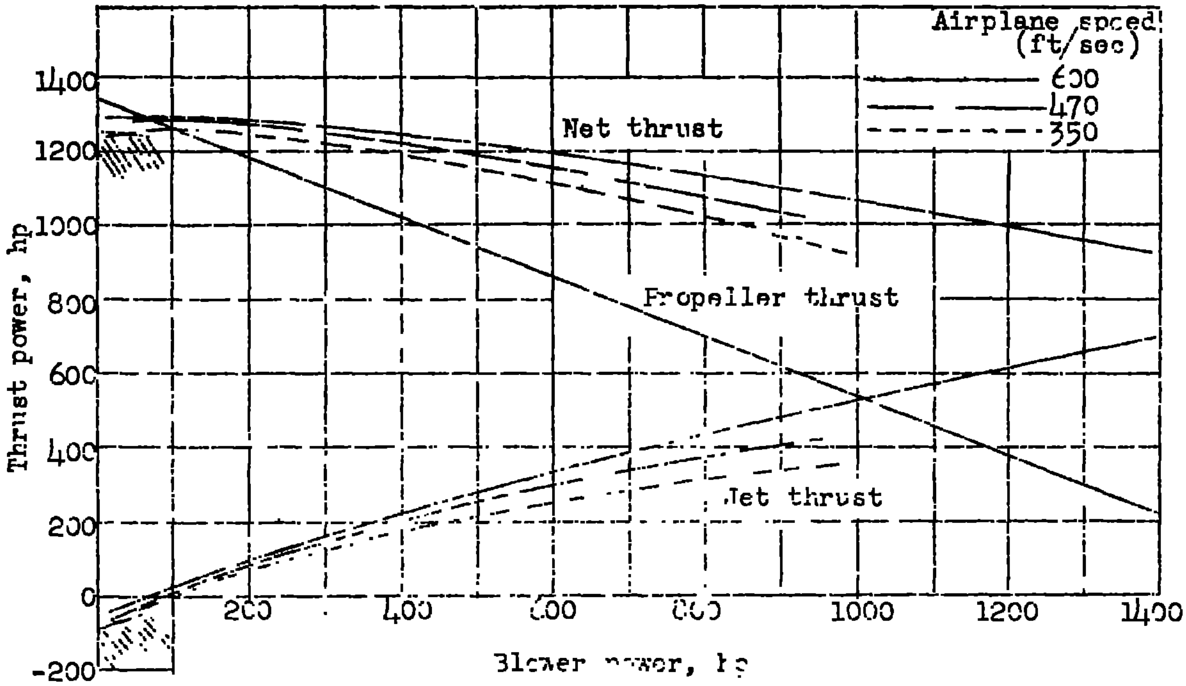


Figure 12.- Thrust as a function of speed and blower power at an altitude of 25,000 feet.

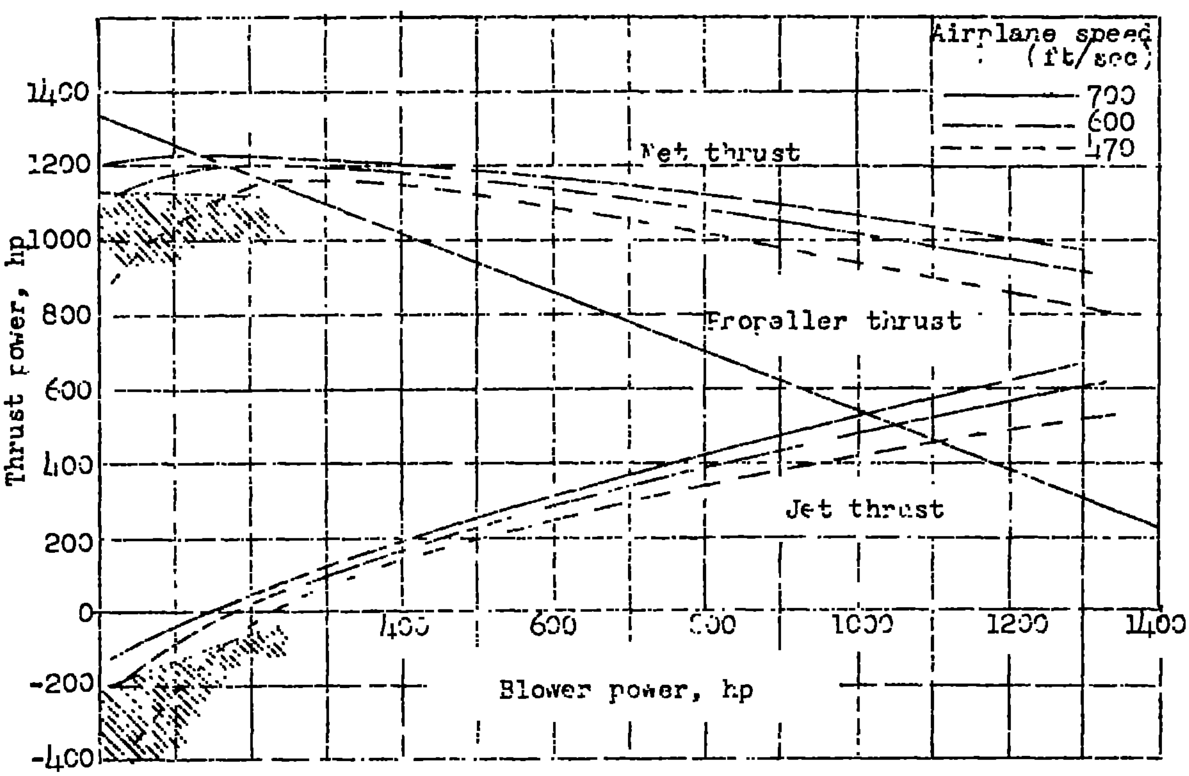


Figure 13.- Thrust as a function of speed and blower power at an altitude of 40,000 feet.

Figures 14 and 15 give the thrust-power breakdown curves for three fin widths in the high-speed condition at sea level, and for two fin widths at 40,000 feet. The narrow fin width is omitted at 40,000 feet because its cooling is quite inadequate under all conditions at this altitude.

Figure 16 shows how the exit velocity varies with blower power. As lower blower powers (lower compression ratios) are used, the velocity out the exit drops rapidly. As this velocity drops, the exit area must increase proportionally. The curves are cut off arbitrarily at an exit area of 5 square feet, that is, at exit velocities of about 300 feet per second at 40,000 feet and 160 feet per second at 25,000 feet, and it is assumed that an

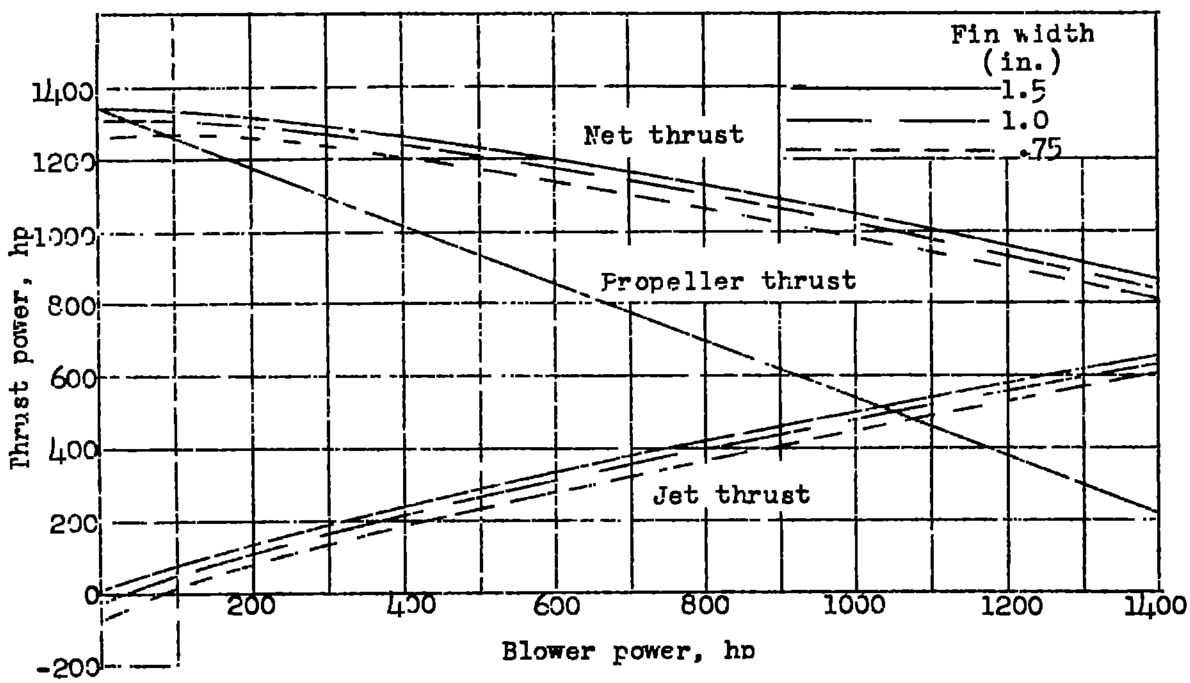


Figure 14.- Thrust as a function of fin width and blower power for high speed at sea level.

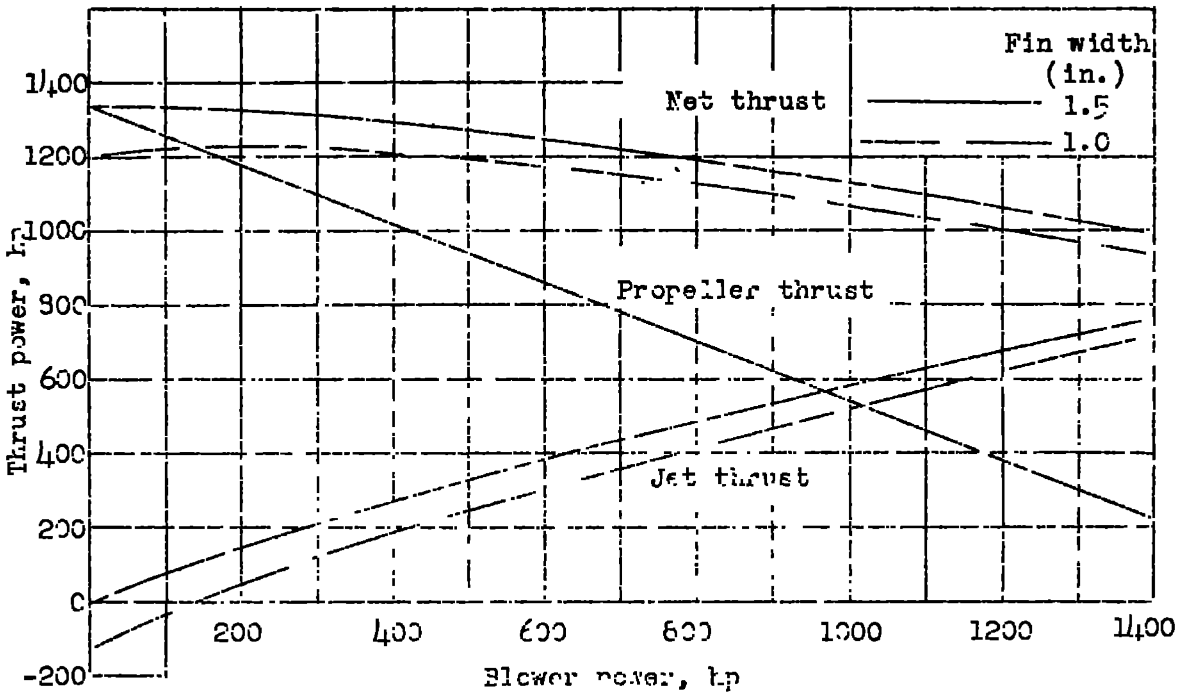


Figure 15.- Thrust as a function of fin width and blower power for high speed at 40,000 feet.

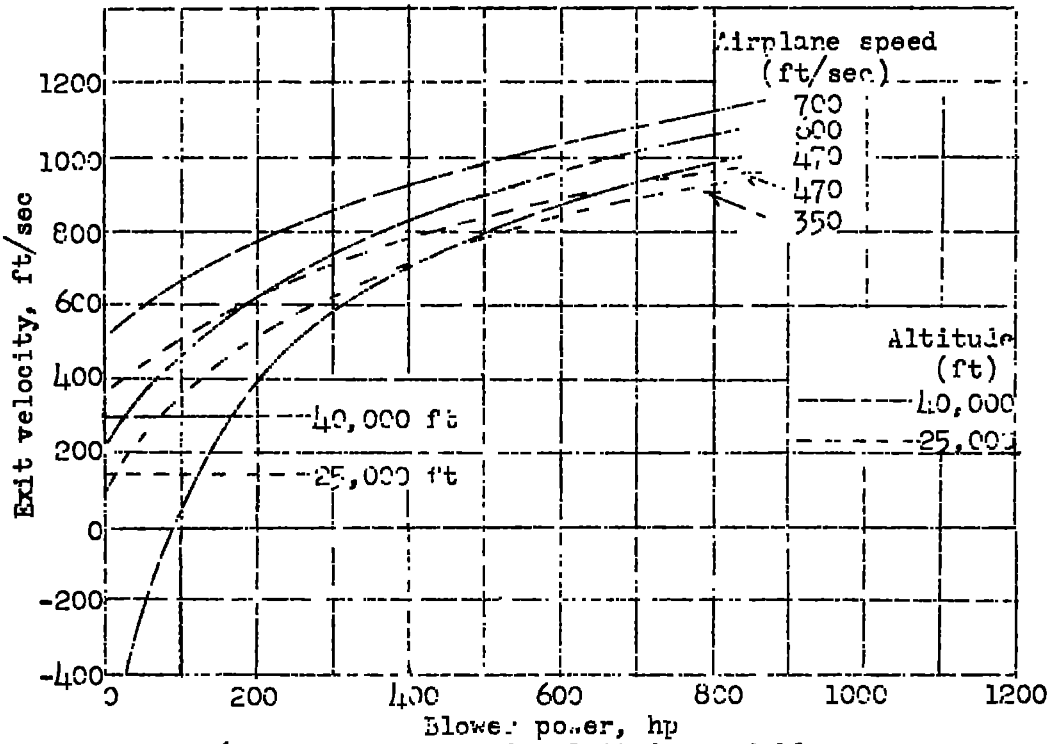


Figure 16.- Effect of speed, altitude, and blower power on cooling-air exit velocity.

engine requiring a greater exit area has insufficient cooling. The shaded areas on some of the figures (for example, figs. 1 and 4), which indicate conditions for insufficient cooling, were determined in this manner. On operating airplanes the area of the exit is further increased by flaps, which may reduce the pressure behind the engine by their effect on the air flow over the nacelle. Rapid drag increases usually accompany the use of flaps beyond some moderate opening, and rather than bring this varying drag condition into the computations the exit area has been limited to the value given previously.

The rate of climb or dive is computed from the difference between the thrust power available and the thrust power required for level flight. The rates of climb at three altitudes are shown in figures 17, 18, and 19.

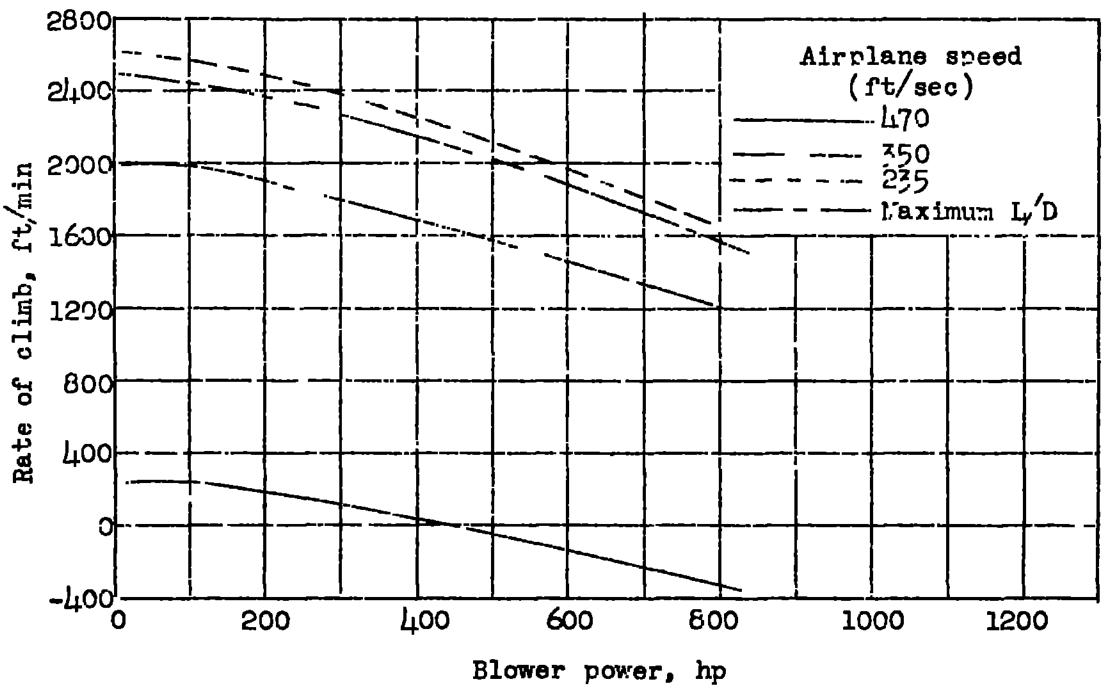


Figure 17.- Rate of climb at sea level.

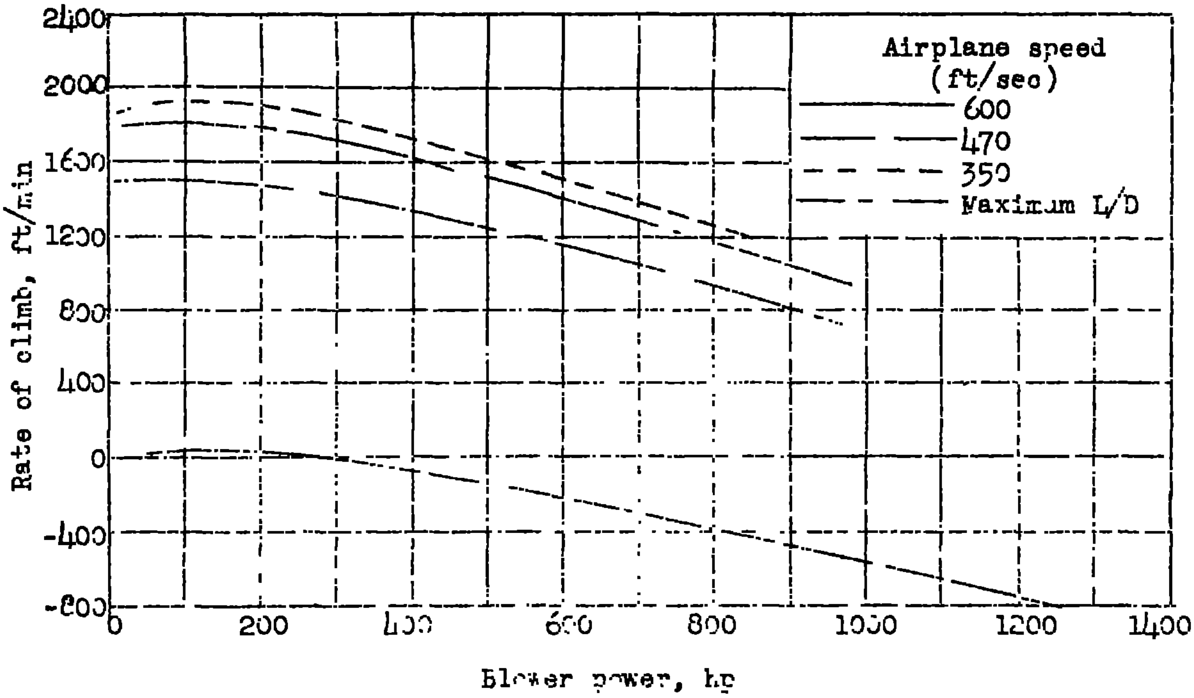


Figure 18.- Rate of climb at 25,000 feet.

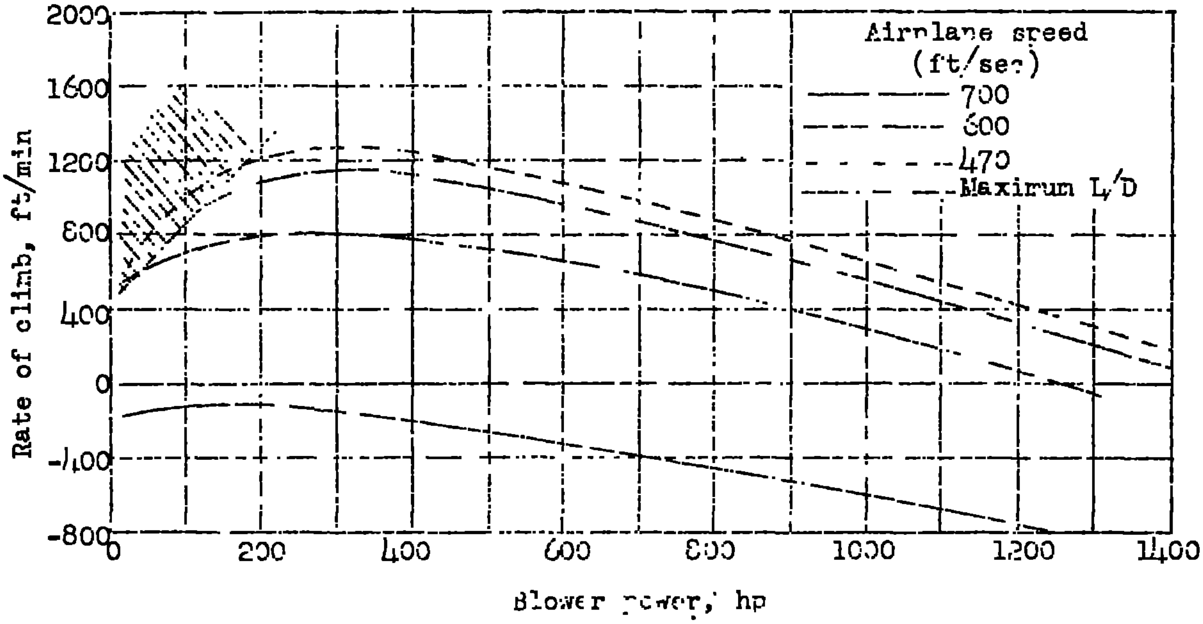


Figure 19.- Rate of climb at 40,000 feet.

Figure 20 shows the effect of the adiabatic efficiency of the blower on the variation of net thrust power with blower power. These curves show that, as the blower efficiency is lowered, the blower power giving maximum thrust decreases very rapidly.

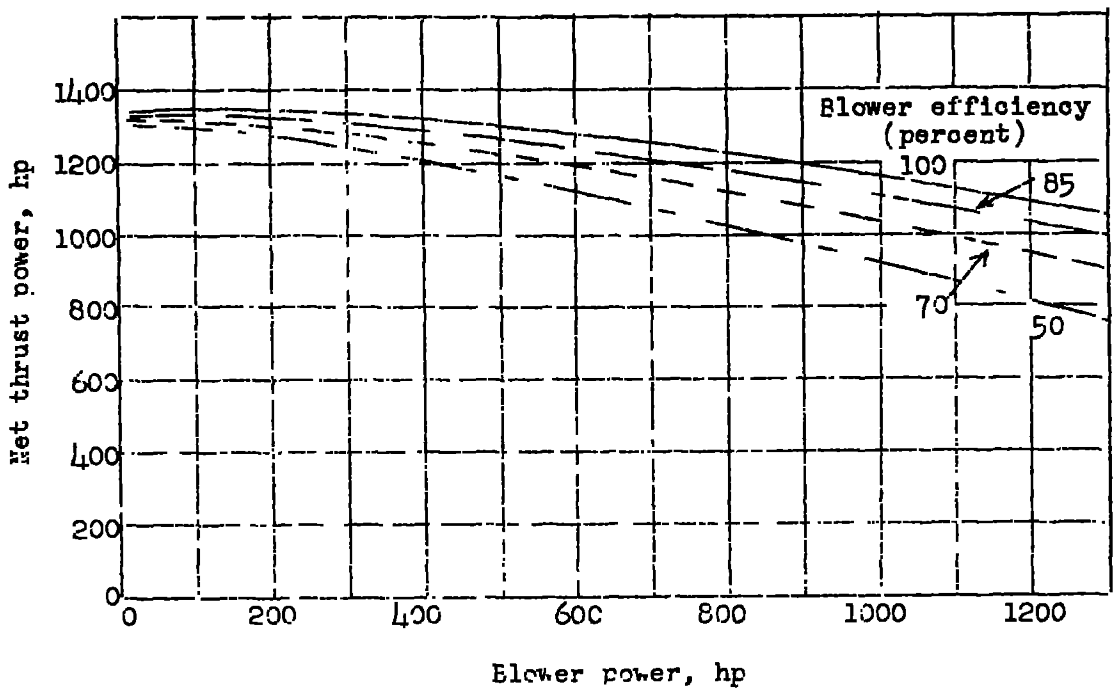


Figure 20.- Effect of blower efficiency on net thrust power for high speed at sea level.

The effect of propeller efficiency is shown in figure 21. The jet-thrust curve for low speed at 40,000 feet and propeller curves for 50- and 80-percent efficiency are used. The effect of decreasing the propeller efficiency is to lower the low-blower-power end of the net-thrust curves and thus to allow more power to be used in the blower to get maximum net thrust power. As is to be expected, the net thrust is quite sensitive to propeller efficiency with low blower power and to blower efficiency with high blower power.

Figure 22, which shows the effects of altitude and airplane speed on the thermodynamic efficiency of the cooling-air heat cycle, complements figure 9, which shows the effects of blower efficiency and fin width. It should be noted that at high altitudes the cycle efficiency is lower than at low or medium altitudes, and the efficiency at low speeds is lower than at high speeds. The airplane speed is of minor importance at low altitudes.

The graphs of thermodynamic efficiency (figs. 9 and 22) invite a further discussion of the heat cycle from a thermodynamic standpoint. The primary object of many heat cycles is to transform heat energy into mechanical energy. When the working substance goes through a closed cycle of conditions, by reversible changes, the area inclosed on a temperature-entropy chart is a measure of the transition between the heat and mechanical forms of energy. A net positive area (circumscribed in a clockwise direction) indicates a gain in mechanical energy. Whenever any part of the cycle is irreversible, the inclosed area no longer has quantitative significance and the entropy rise becomes of importance. In such cases the only areas of particular significance are outside the cycle.

When irreversible changes (for example, friction heating) occur, the cycle may be drawn on an enthalpy-entropy chart and the mechanical and heat energies read from distances rather than areas. In this case the problem is that of putting the point 5 (figs. 23 to 27) as far below the total-energy level for the exit as possible. When this separation is increased by raising the total energy with a blower, it is at the expense of propeller power. When point 5 is lowered by keeping the entropy low, the power cost of the change is negligible. This contrast clearly calls for low cooling-air velocity in the heat exchanger and high blower efficiency.

Figures 23 to 27 show several representative cooling-air heat cycles. Figure 23 shows an actual cycle, upon which is superimposed an ideal, or reversible, cycle with the same starting point and energy additions. This ideal cycle (0 1' 4' 5) is inclosed by two constant entropy lines and two constant pressure lines (the Joule or Brayton cycle) and has a positive efficiency. So long as there are no turbulence or frictional pressure losses, this cycle will continue to have a positive efficiency, regardless of the amount of blower compression.

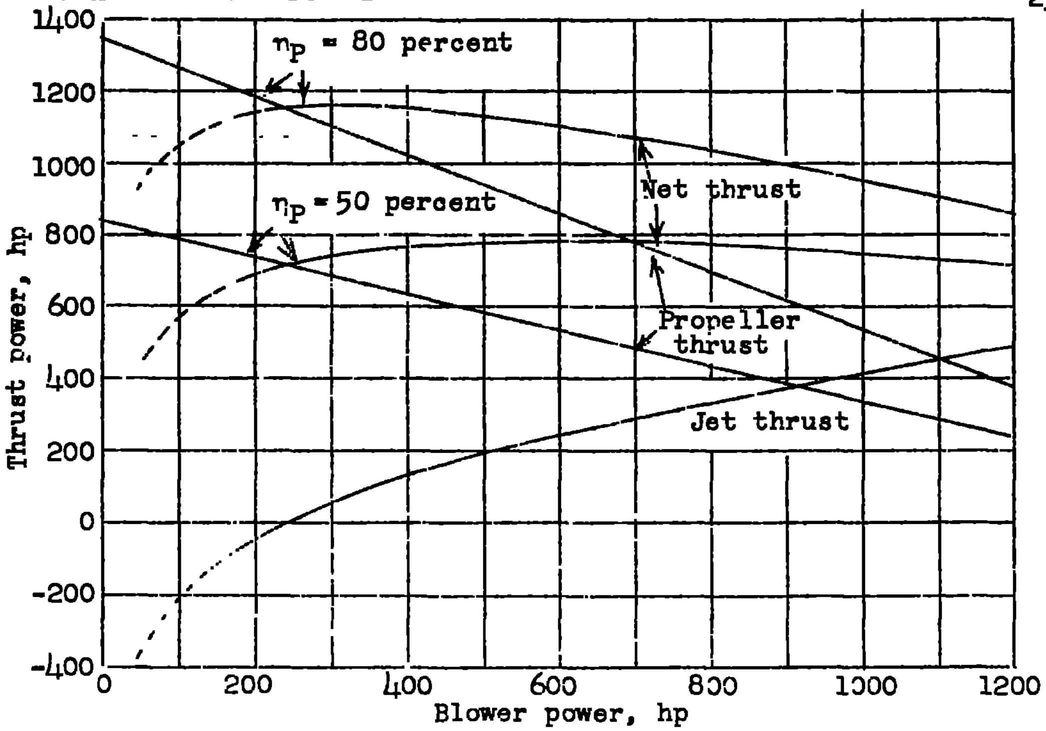


Figure 21.- Effect of propeller efficiency for low speed at 40,000 feet. η_B = 70 percent.

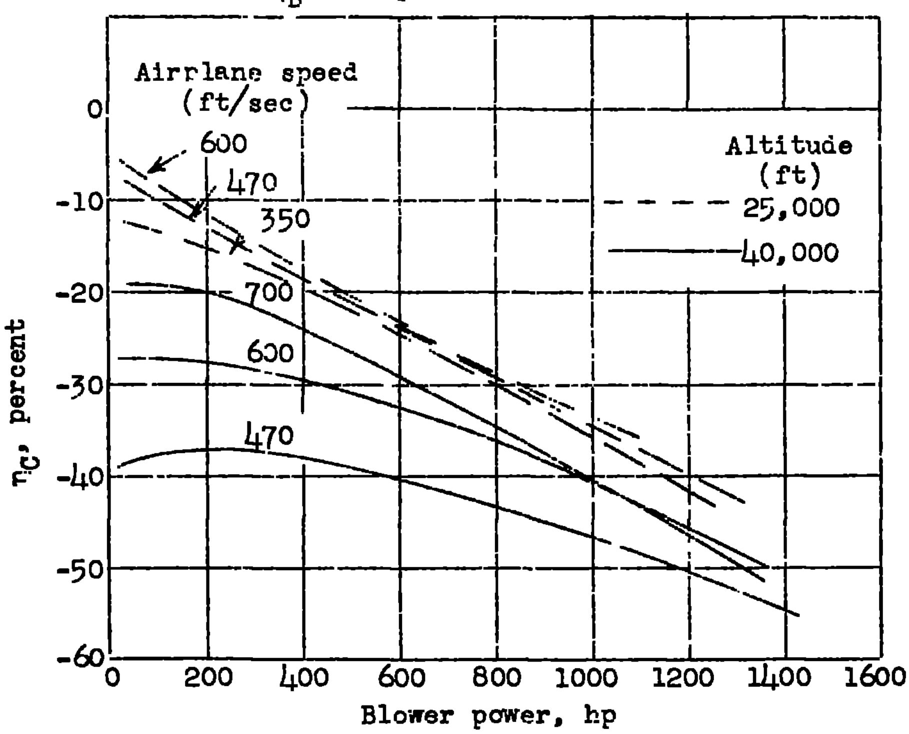


Figure 22.- Thermodynamic efficiency of cooling-air heat cycle for three airplane speeds at two altitudes. η_B = 70 percent.

A small increase in entropy, however, raises point 5 enough to cause a net loss in mechanical energy.

Figure 24 shows a cycle that is idealized to the extent of allowing a 100-percent-adiabatic efficiency for the blower. Velocity in the fins is low enough that there is little pressure drop in the fins, and for the cycle there is a slight gain in mechanical energy. In this case cooling is no problem.

Figure 25 goes to the opposite extreme and shows a cycle for which the cooling is insufficient. In this case the velocity in the fins is high, thus causing considerable pressure drop and moving point 3 far to the right. This high air velocity also leads to large losses in total pressure (entropy rise) when the air is dumped from the fins. As a result, if the required rate of cooling-air flow were to exist, the total pressure behind the fins would be lower than the free-stream static pressure and the cycle would be impossible without the use of flaps. In the case of narrow fins at 40,000 feet, the cooling situation is so bad that the point 3 cannot be defined for any amount of compression and it is impossible to complete the cycle. Obviously, wide fins are necessary to keep the entropy rise at a minimum. This fact is even more apparent from a comparison of figures 26 and 27, which show the cooling-air cycle for ram compression with two different fin widths. These figures show that the air going through the 1.5-inch fins has twice as much kinetic energy at the exit as the air through 1.0-inch fins.

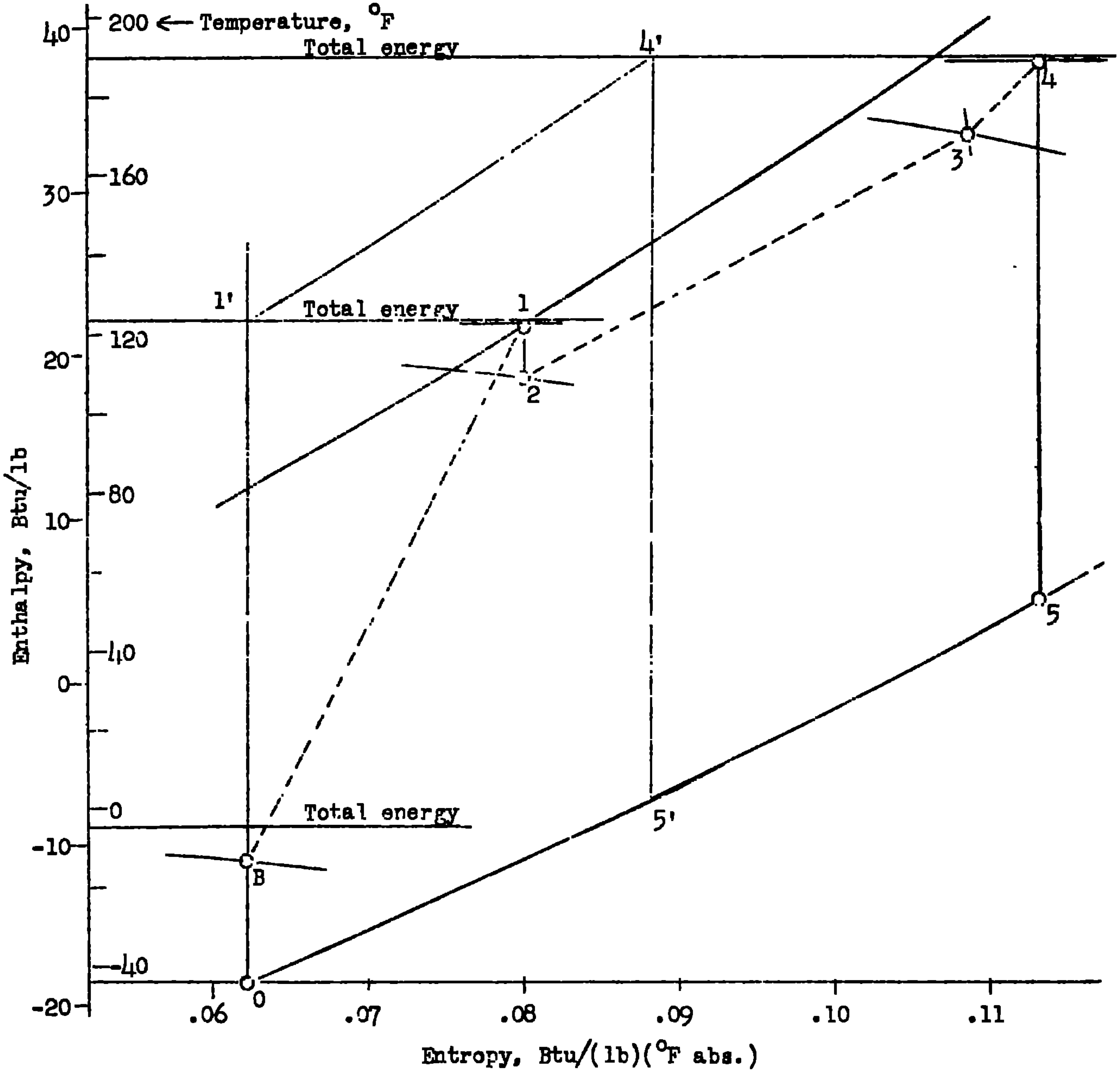


Figure 23.- Cooling-air heat cycle for high speed at 40,000 feet. η_B = 70 percent; Δp_B = 3.5 pounds per square inch.

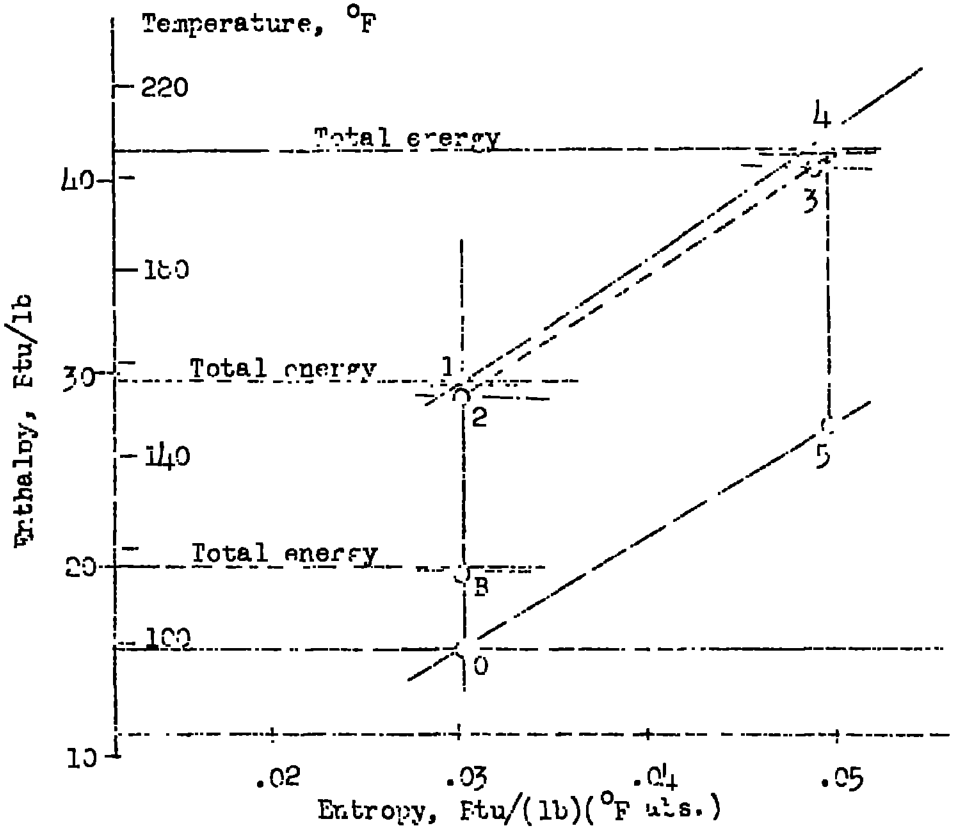


Figure 24.- Cooling-air heat cycle for high speed at sea level. η_B = 100 percent; Δp_B = 4.17 pounds per square inch.

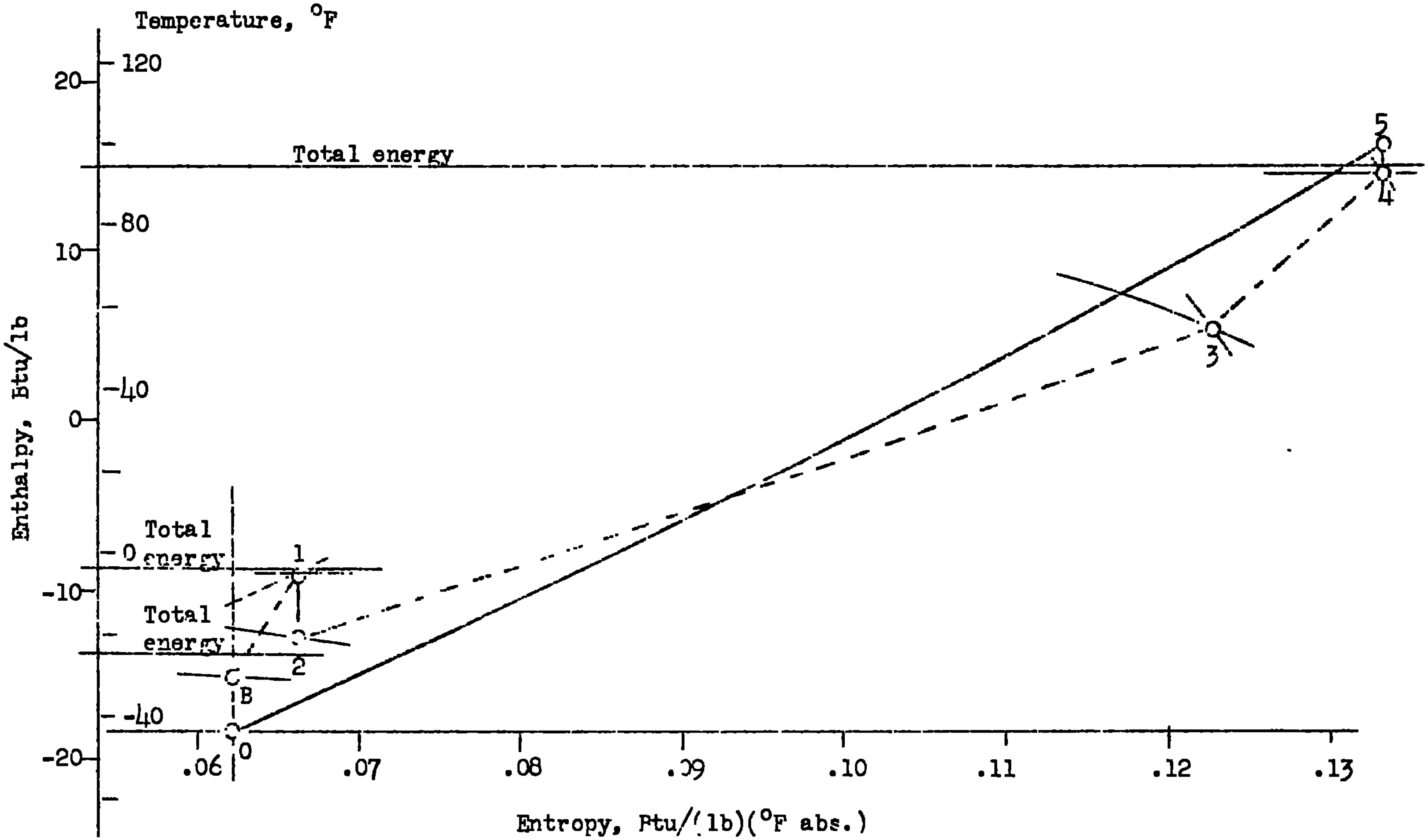


Figure 25.- Cooling-air heat cycle for climb at 40,000 feet. η_B = 70 percent; Δp_B = 0.47 pounds per square inch.

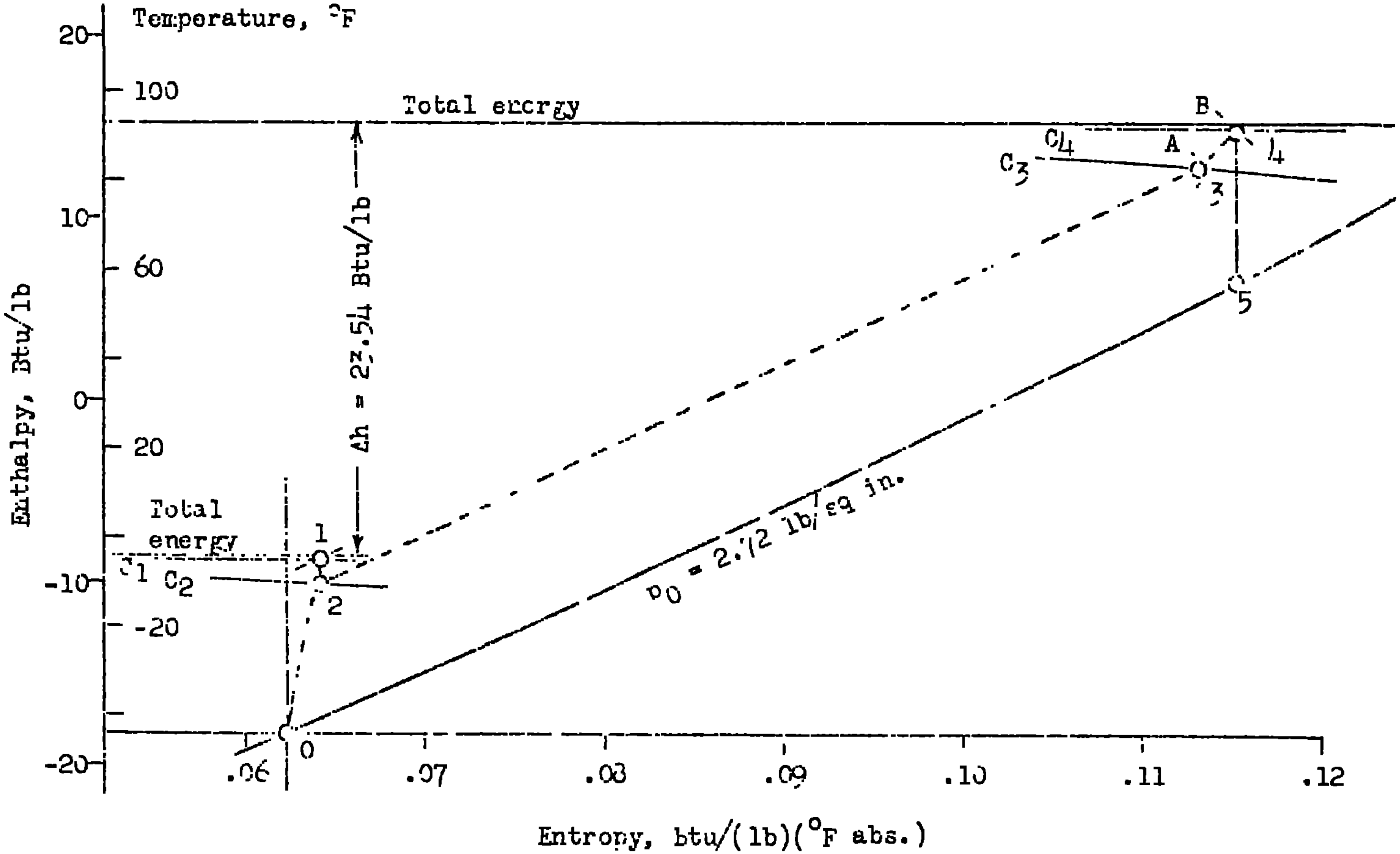


Figure 26.- Cooling-air heat cycle with ram compression for high speed at 40,000 feet. Fin width, 1.5 inches.

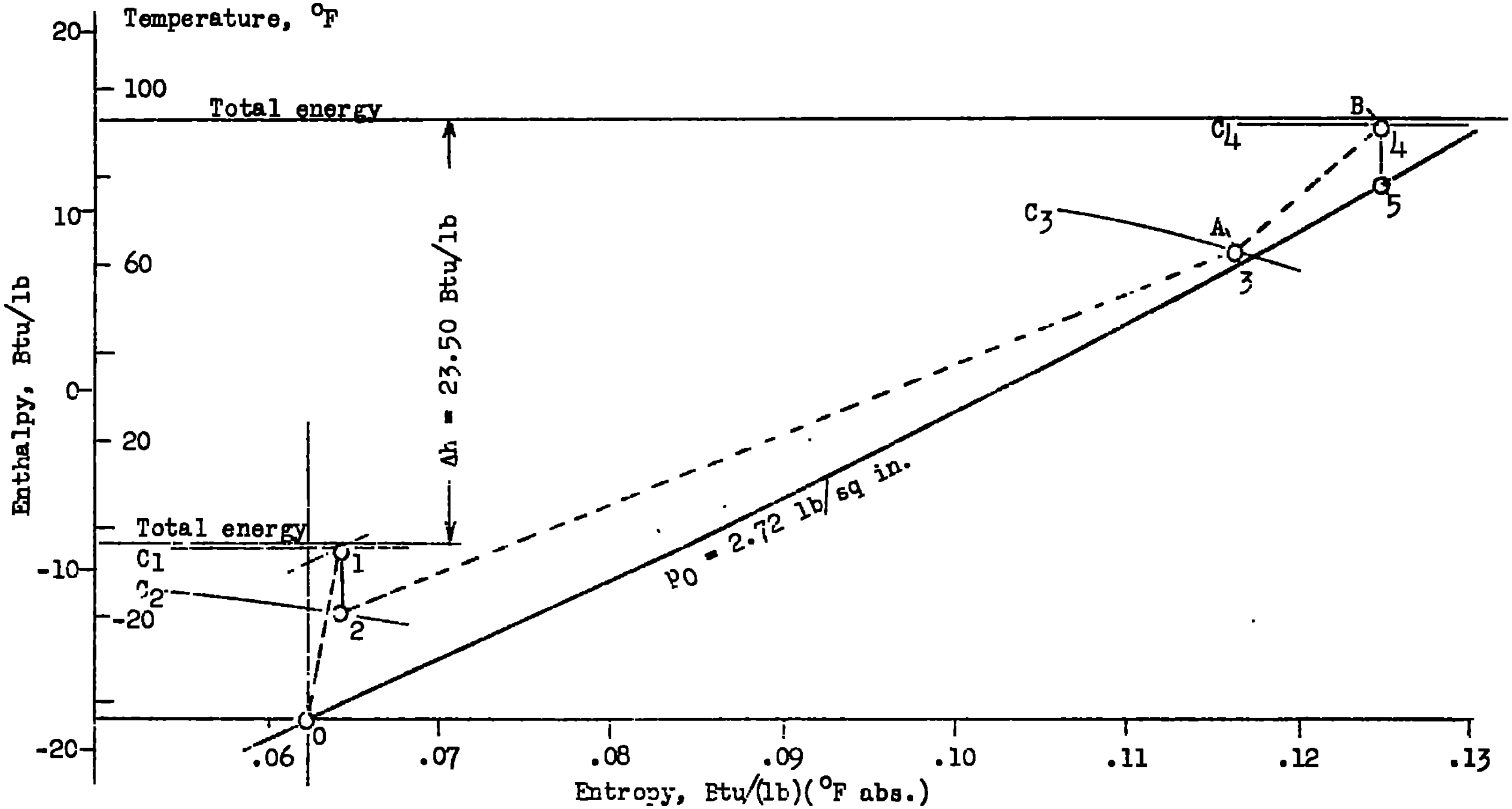


Figure 27.- Cooling-air heat cycle with ram compression for high speed at 40,000 feet. Fin width, 1.0 inch.

APPENDIX C

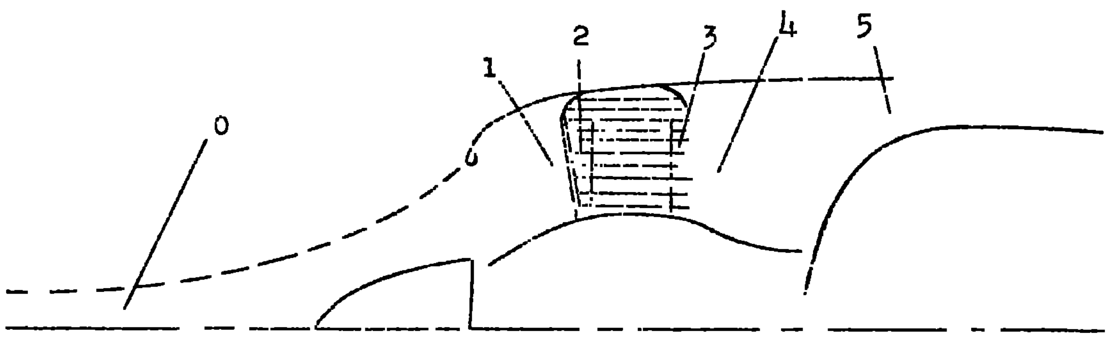
METHOD OF CALCULATION

Case 1 - Ram Compression

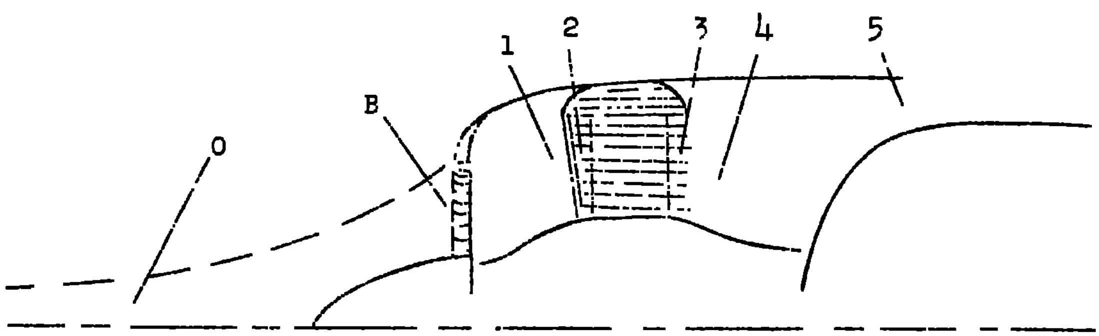
The results presented in this analysis were obtained by graphical solution with charts like figure 28 (placed at end of report). (In the preparation of fig. 28 the equation for specific heat at constant pressure

$$c_p = 0.2412 + \frac{0.0008T}{100}$$

was used. This equation is derived from a curve of c_p plotted against T in reference 3.) The stations in the cooling system are shown in figure 29. Sample



Case 1 - Ram compression



Case 2 - Blower compression

Figure 29.- Stations in cowled heat exchanger.

solutions are shown in figures 26 and 27. Figure 26 will be explained in detail by figures 30 to 33.

It will be observed in figure 28 that lines of constant pressure and constant specific volume are plotted on a coordinate system of entropy and enthalpy or temperature. Any point on the chart represents a certain temperature, pressure, and specific volume. When a determination of the power to cool an air-cooled engine is made, the temperature and pressure in the free air stream locate the starting point on the chart. For the typical case used, this initial point is indicated by O in figure 30.

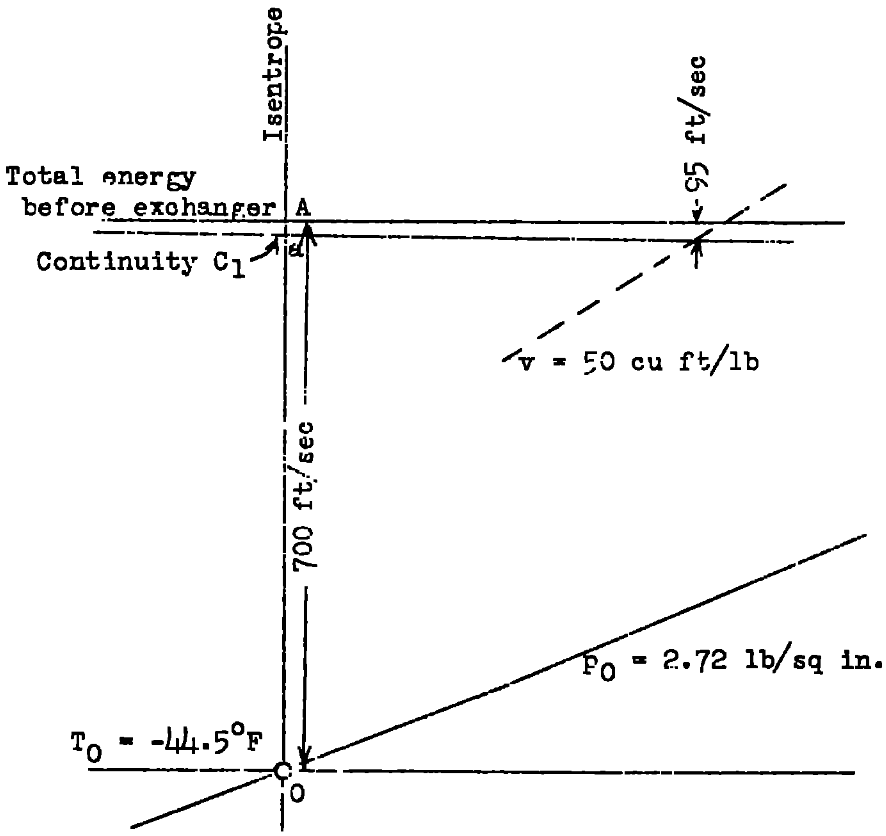


Figure 30.- Entrance section; continuity line construction.

Cowling entrance.- The air has a speed of 700 feet per second with respect to the cowling, and the kinetic energy associated with this speed must be considered as increasing the free-stream total energy. The insert in figure 28, when drawn to proper scale, shows this kinetic energy in enthalpy units. The value is taken from the insert with dividers and set off vertically above 0 on the chart to establish the point A (fig. 30). A horizontal line through A indicates the total-energy level of the air relative to the cowling at any time before the air enters the heat exchanger. In entering the cowling the air slows down, the temperature and the pressure rise, and the specific volume decreases. Point A would be the state point of the air if it were brought exactly to rest relative to the cowling, and if this were done at 100-percent efficiency without heat being gained or lost.

Because in practice the air may not be entirely stopped, it is necessary to apply the condition that the weight of air passing through the system be constant; thus

$$W = \frac{A_1 V_1}{v_1}$$

The weight rate of flow is established by cooling requirements and the cross-sectional area just before the heat exchanger is known from the geometry of the system. Select a specific-volume line in the vicinity of A (for example, 50 cu ft/lb) and calculate the corresponding velocity (95 ft/sec). Measure off on the inserted velocity-energy scale the distance corresponding to this velocity. Where the specific-volume line is this distance below the total-energy line, plot the point. Several of these points determine the continuity line C_1.

The point a on line C_1, just below point A, is the state point of the air if the prescribed amount of air flows through the system at 100-percent efficiency and with no heat gained or lost. The physical significance of points A and a is as follows: Point A describes the physical properties of the air just in front of the engine when no air is allowed to flow through the fins. Point a describes the physical properties of the air in front of the engine when the air is slowed down but not entirely stopped. The distance between points A and a gives the velocity of the slow-moving air just before it accelerates into the engine fins.

The ram compression of the air within the cowling, however, is actually accomplished at some lower efficiency and, therefore, the point must fall on some lower pressure curve than the one through point a. (See fig. 31.) The new pressure curve is defined by the relation

$$\eta_R = \frac{\Delta p_{actual}}{\Delta p_{isentropic}}$$

where $\eta_R = 90$ percent is assumed and the isentropic pressure rise is the pressure difference between points 0 and a. The value of Δp_{actual}, which is calculated from this equation, is the pressure rise that will actually occur from free stream to a point just before the

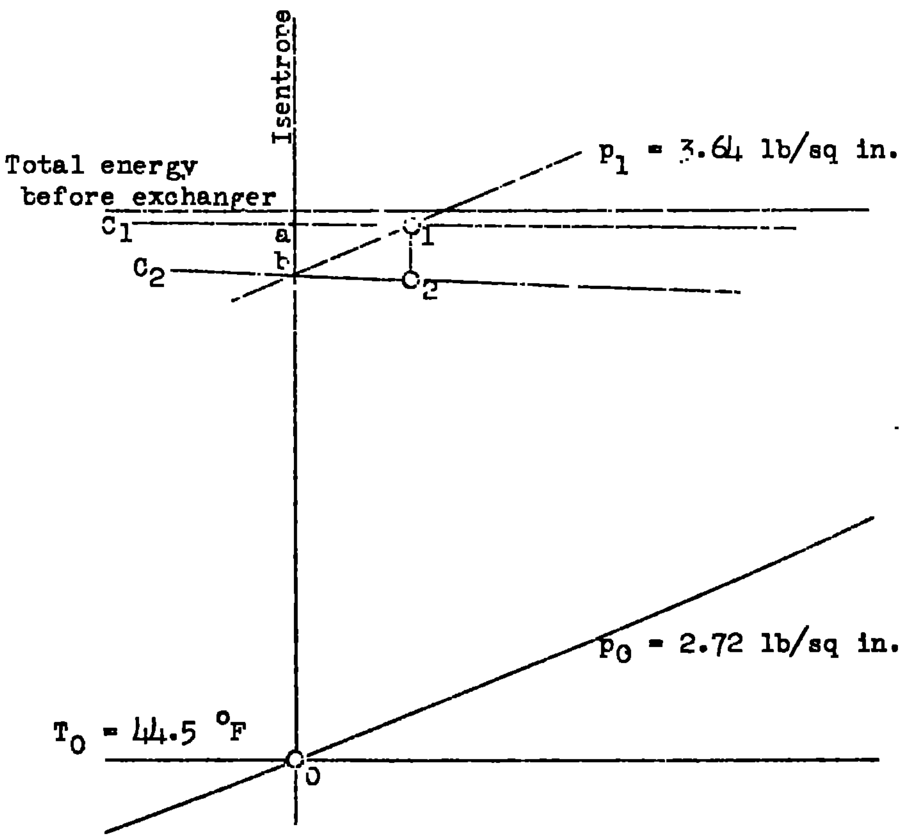


Figure 31.- Diffuser and heat-exchanger entrance.

engine and establishes the pressure line p_1 through the point b. (This pressure line p_1 may also be located very easily, and with only slight error, by laying off Ob equal to 90 percent of Oa.) The state point for the air in front of the engine must lie somewhere on this pressure line. Inasmuch as conservation of mass applies to air flowing through the cowling, the state point must also lie on the continuity line C_1. The state point 1, which describes the physical properties of the air at the maximum open section of the cowling (station 1, fig. 29), therefore is at the intersection of p_1 and C_1. The vertical distance between state point 1 and the total-energy line measures the velocity.

Entrance to fins.- When the air enters the fins, the constriction of the air stream causes the velocity to increase and the static pressure and temperature to decrease. On the chart, therefore, the state point for the air in the heat-exchanger entrance will be somewhere below that for the air in front of the exchanger. The exact location is determined as follows:

By use of the constant-weight-flow requirement

$$W = \frac{A_2 V_2}{v_2}$$

the continuity line C_2 is drawn in the same manner as C_1. The state point of the air just after entering the fins must lie on this line. Because good baffle entrances allow the air to accelerate at nearly 100-percent efficiency (no entropy change), a vertical line is dropped from state point 1 to the line C_2. The intersection is the state point 2, which completely describes the physical properties of the air just after it enters the fins but before it has been heated by the fins. The air velocity is measured by the distance between the total-energy line and the point 2.

Heat exchanger.- When the cooling air goes through the fins, its temperature rises and the state point therefore must rise on the chart. There is also some decrease in pressure and increase in specific volume. In order to describe such a change in properties, the state point must rise and move to the right on the chart.

The method for locating the point exactly is shown in figures 26 and 32. The heat energy added to each pound of cooling air

$$\Delta h = H/W$$

is the amount that the total-energy level rises as the air takes heat from the fins. This rise is set off as shown in figure 26. The line C_3 is drawn below this new total-energy level (fig. 32) exactly as C_1 and C_2 were drawn below the first energy-level line. These continuity lines show what part of the total energy is in thermal energy and what part in kinetic energy at various pressures and specific volumes.

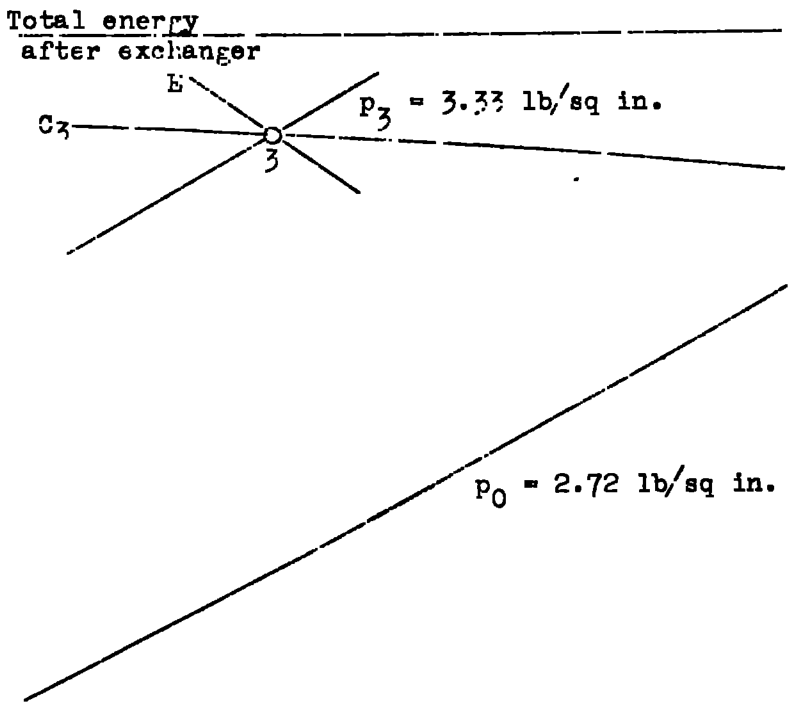


Figure 32.- Heat exchanger.

The equation

$$p_2 - p_3 = \frac{0.3V_2}{2v_2 g}\left(\frac{V_2 + V_3}{2}\right) + \frac{V_2}{v_2 g}(V_3 - V_2)$$

is used to determine the pressure of the air just before it leaves the fins. The first term on the right-hand side, for frictional pressure drop, is taken from reference 1; the second term is the momentum pressure drop. When put into the form

$$p_3 = p_2 + \frac{W}{A_2 g}\left(0.925V_2 - 1.075V_3\right)$$

it is easy to evaluate p_3 in terms of V_3. This equation is plotted in exactly the same manner as the continuity equations, except that pressure and velocity are used instead of specific volume and velocity. This pressure line is shown as line E in figure 32. The intersection of lines E and C_3 is the state point 3 and describes the only combination of properties possible for the air just before it leaves the fins. This set of properties is uniquely determined by the equations for pressure drop and by the fact that the weight rate of air flow is constant from the entrance to the exit of the cowling.

Exit from heat exchanger.- The change in the condition of the air as it leaves the fins is shown in figure 33. When the air entered the fins, it was accelerated very efficiently. In contrast, there is much turbulence produced in the air when it is dumped abruptly into the open space behind the engine cylinders. This turbulence decreases the amount of dynamic pressure that can be converted into static pressure. Instead of describing this loss with an efficiency factor, the usual expression for loss in total pressure at an abrupt expansion is used:

$$\Delta \text{ Total pressure} = \left(1 - \frac{A_3}{A_4}\right)^2 \frac{V_3{}^2}{2v_3 g}$$

In terms of velocities and static pressures this expression is

$$p_4 = p_3 + \left[\frac{2A_3}{A_4} - \left(\frac{A_3}{A_4}\right)^2\right]\frac{WV_3}{2A_3g} - \frac{WV_4}{2A_4g}$$

The requirement of constant weight flow allows the continuity line C_4 to be drawn on the chart, and enough of the pressure equation just given is plotted (line F) to intersect the continuity line. The location of the state point 4 shows that only a small amount of static pressure is regained in the expansion and that the temperature rise is almost the same as would have resulted from an efficient expansion. The increase in entropy during the expansion is a measure of the energy that has become unavailable for doing mechanical work and is tied up in undirected turbulence.

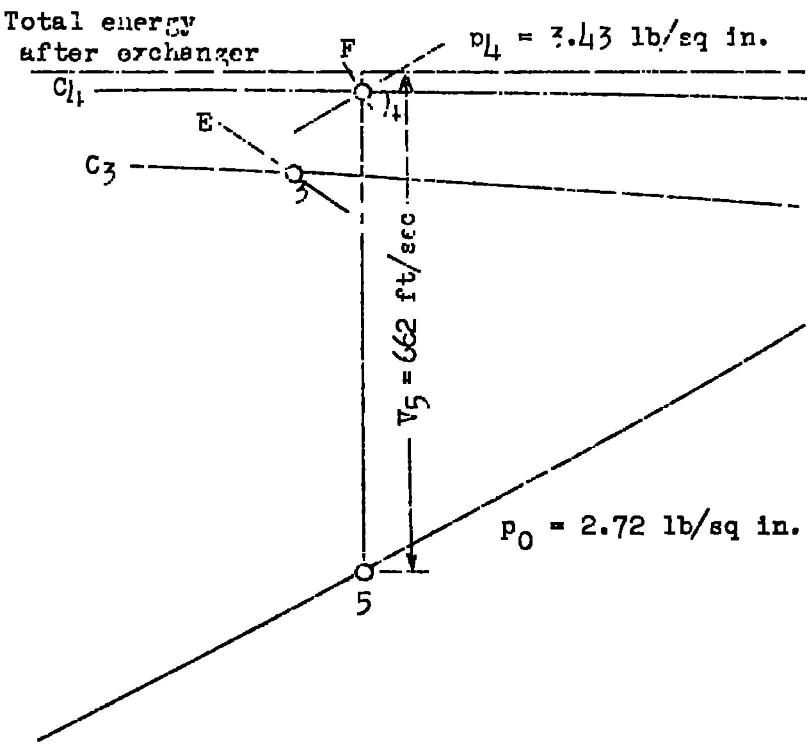


Figure 33.- Exit from exchanger and duct.

Exit from cowling.- The path of the air inside the cowling converges as it goes from the large area behind the engine to the exit and the pressure drops to free-stream static pressure at the exit. As the air is accelerated by this pressure drop, the temperature also drops and the specific volume increases. This is the same effect as the acceleration of the air into the fins between stations 1 and 2 and is assumed to take place at 100-percent efficiency. On the chart (fig. 33) this change is described by dropping a vertical line from the state point 4 to intersect the free-stream pressure line, which passes through the free-stream state point 0. The state point 5 describes the temperature and the specific volume of the air as it leaves the cowling, and the distance between state point 5 and the total-energy line tells the velocity of the air in the exit.

The air originally had a velocity of 700 feet per second relative to the cowling but at the exit its velocity was only 662 feet per second. This negative velocity change is substituted in the equation

$$P = \frac{WV_0 \Delta V}{550g}$$

to find the jet thrust horsepower. When V is negative - that is, when the air is slowed - the equation for P gives the power required to overcome the "momentum drag" of the cooling air.

Case 2 - Blower Compression

When a blower is used to give a higher pressure in front of the engine, the calculations for the cowling entrance are changed somewhat. The blower is placed at the cowl entrance and, as there is little opportunity for friction or breakaway, the ram compression in front of the blower is assumed to take place at 100-percent efficiency. Describing this compression on the chart in figure 34, the state point moves vertically upward from 0 to the proper pressure. In order to locate the state point exactly, the blower continuity line C_B is drawn, using the 4-square-foot open area of the blower and the

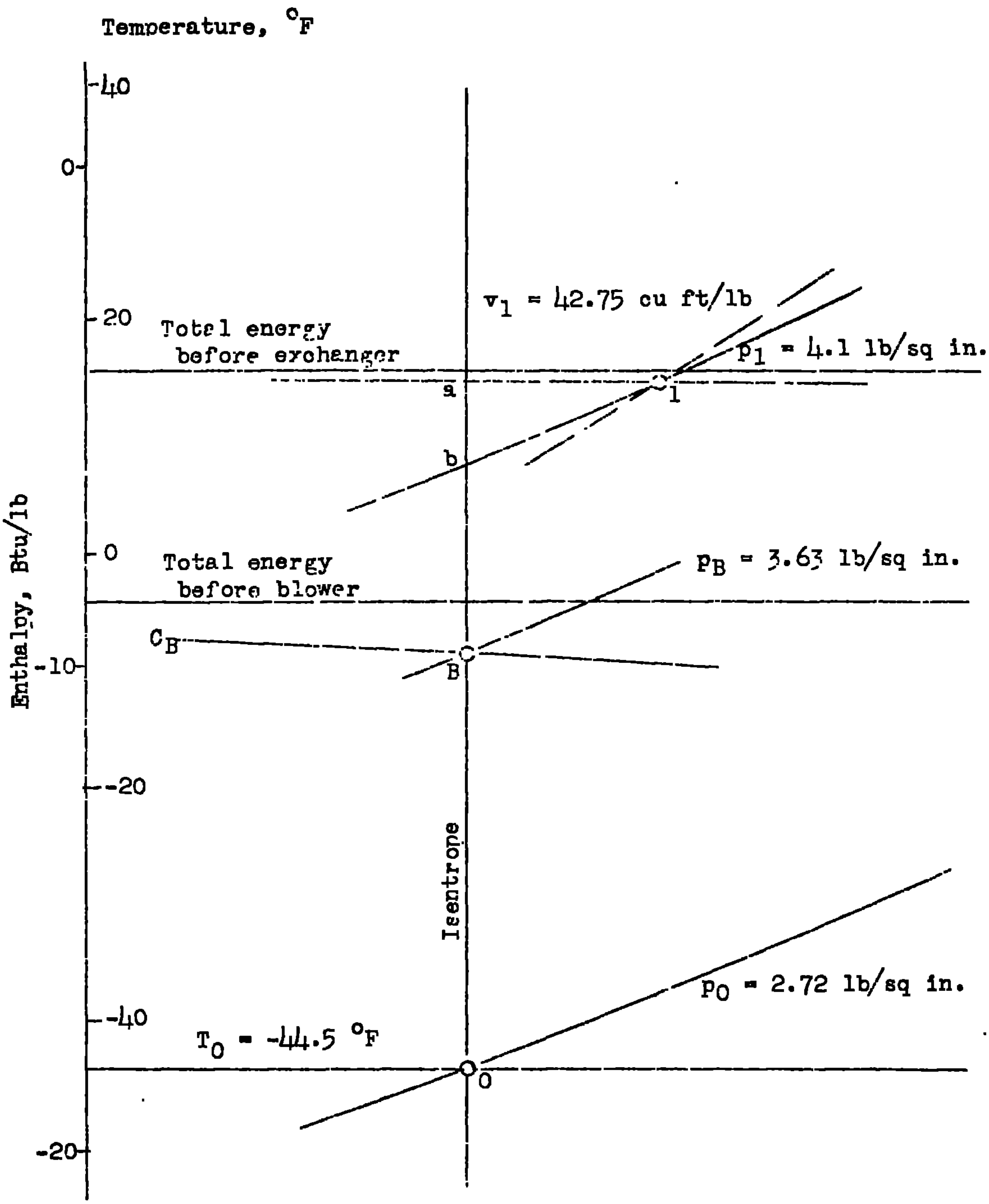


Figure 34.- Entrance section with blower.

required weight flow. The intersection of C_B and the vertical line through O is the state point B describing conditions just in front of the blower.

The static-pressure rise desired over the blower-diffuser section is added to the pressure at point B to find what the pressure will be just in front of the engine. This pressure line, $p_1 = 4.1$ pounds per square inch, in the example (fig. 34) is drawn in. The state point 1 must lie somewhere on this pressure line because of the defined pressure rise. The particular point on the pressure line is determined by the efficiency in this manner:

Define the adiabatic efficiency of the blower as

$$\eta_B = \frac{\Delta h_{isentropic}}{\Delta h_{actual}}$$

Mark the point b where the p_1 line intersects the vertical line, or isentrope, through O and B. If the blower and diffuser were 100-percent efficient, the point b would be state point 1; therefore, the isentropic enthalpy change $\Delta h_{isentropic}$ is the enthalpy rise from point B to point b. Use $\eta_B = 70$ percent to calculate the actual enthalpy rise. This actual increase in enthalpy establishes the point a, which is at the temperature existing just before the engine. The horizontal (constant temperature) line through point a intersects the line p_1 at state point 1. Physically, the following happens: The blower puts more energy into the air than is necessary to get the desired pressure rise and part of this energy goes into raising the temperature. The isentropic enthalpy rise is the minimum energy that can be used to get the desired pressure rise. The difference between the isentropic and the actual enthalpy rise is the thermal energy that appears from friction and the damping out of turbulence.

Because the state point 1 must lie on the continuity line C_1 (not drawn here), the continuity equation is solved for velocity by using the specific volume at point 1, and the distance corresponding to this velocity is laid off above 1. The total-energy line passes horizontally through the new point. This energy line defines the total-energy level just in front of the engine and is used to calculate state point 2 and all the rest of the cycle exactly as was done for ram compression.

The difference between the total-energy levels in front of the blower and just in front of the engine is the energy put into each pound of air by the blower. The total power cost of the blower then is

$$\frac{1.414W \, \Delta h_B}{\eta_S}$$

where η_S is the shaft efficiency for transmitting power from the engine to the blower and Δh_B is the total-energy rise over the blower.

APPENDIX D

CONDITIONS UPON WHICH CALCULATIONS ARE BASED

For most of the problems associated with cooling an air-cooled engine an exact solution is impossible and somewhat idealized conditions must be defined as a basis for calculation. The conditions for the present report are given and an evaluation made of the degree of approximation involved to aid in comparing these results with those obtained by other investigators.

The performance of the airplane is described by the L/D curve in figure 35, which is taken from an unpublished analysis.

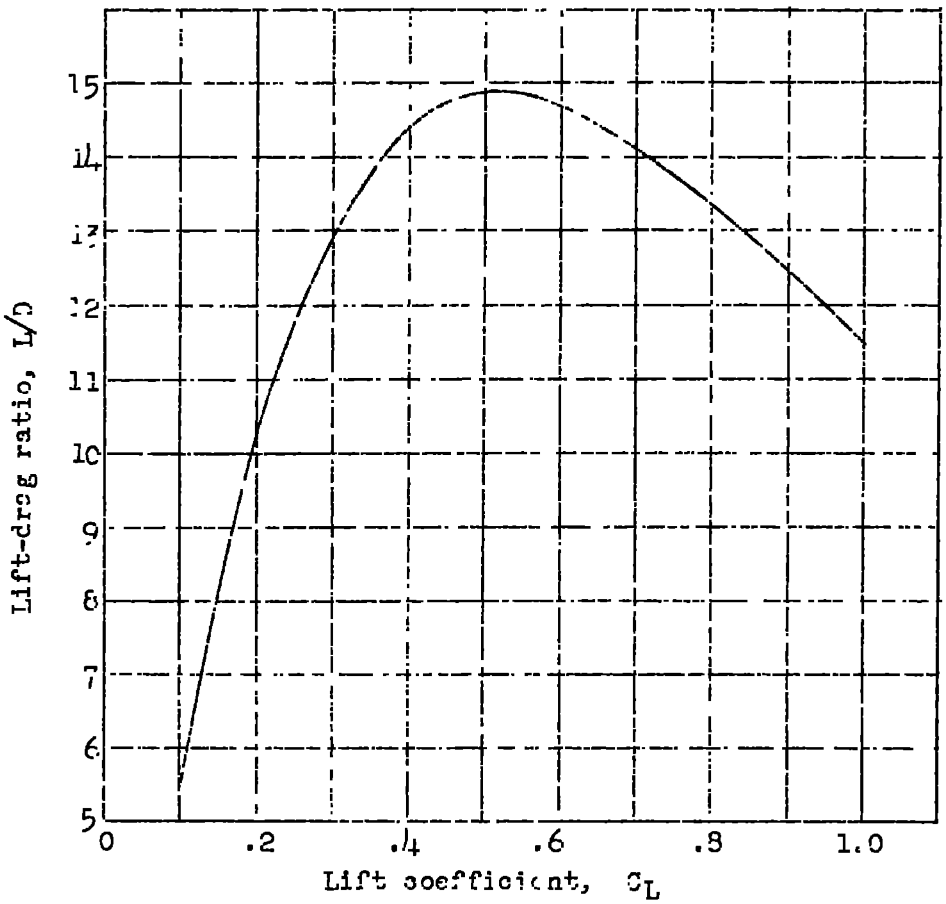
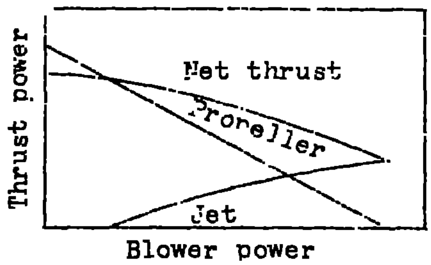


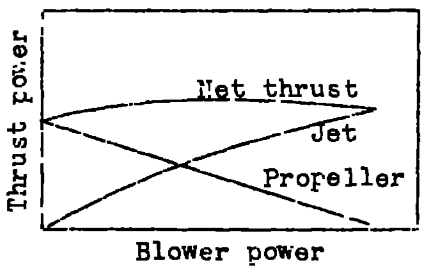
Figure 35.- Lift-drag ratio of airplane as a function of lift coefficient.

The hypothetical engine considered, like that in reference 1, develops its normal power rating of 1675 horsepower under all conditions, and all of this power that is not used to operate the blower is put into the propeller. The rate of heat dissipation through the cooling fins is 445 Btu per second with an average head temperature of 410°F.

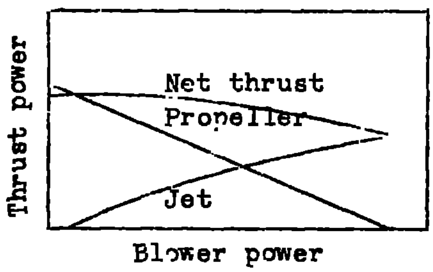
The propeller and blower efficiencies are held constant at 80 and 70 percent, respectively. In this way it is possible to show the effect of a blower on the thrust power for a considerable range of blower powers, fin widths, altitudes, and speeds. In an actual case, however, the efficiencies of the propeller and blower vary throughout the range of normal operation. This actual case may also be analyzed by the methods of this report. The idealization in the assumption of constant efficiencies does not invalidate any of the general conclusions. The accompanying diagrams show the effect of changing the blower and propeller efficiencies.



High propeller efficiency
Low blower efficiency



Low propeller efficiency
High blower efficiency



Average efficiencies

General Conditions

Army air is used exclusively.

Uniform temperature, pressure, and velocity exist over any cross section of the cooling-air duct. The use of mean values for velocity and physical properties introduces no errors beyond the approximations in the equations.

Additional approximations are involved in the neglect of the induced power for the fins and blower, and the induced and operating power for a supercharger. The difference in induced powers, from the narrowest to the widest aluminum fins, is less than 10 horsepower. Blower induced power for all but the largest blowers is of the same order of magnitude. The supercharging requirements are the same for both cooling methods; therefore, the comparisons that have been drawn are still valid.

Case 1 - Without Blower

(Numbers in headings - for example (0 to 1) - indicate stations in the cooling-air duct, as shown in fig. 29.)

Entrance diffuser section (0 to 1):

No heat transfer occurs. Temperature rise due to compression is so small and rate of heat loss so low that, with the flow rates used, the temperature change due to heat transfer is quite insignificant.

Frictional effects are accounted for in the efficiency terms η_R or η_B.

Heat-exchanger entrances (1 to 2):

Air accelerates isentropically. This statement is substantially true for all reasonably well-designed entrances.

No heat transfer occurs. While not strictly true, this assumption involves negligible error. Compression has already taken place and whether a small amount of heat enters the air just before or just after station 2 is immaterial.

Heat exchanger (2 to 3):

Frictional pressure drop in the fins is 30 percent of the average dynamic pressure. This value agrees well with experience and, being held constant, does not invalidate any comparisons.

No other assumptions beyond the general conditions are used in the heat exchanger.

Heat-exchanger exit (3 to 4):

Total-pressure loss is the same as for an abrupt expansion. Mixing losses, where the streams around opposite sides of the cylinder meet, tend to make this loss larger, and baffle exits may be designed to make the expansion less abrupt. Inasmuch as these effects cannot be accurately evaluated and do not differ greatly with or without a blower, they are neglected. The equation used is for incompressible flow but again the error is negligible. With an area ratio of 0.3 and a Mach number of 1, for example, the error is less than 1 percent, and with Mach numbers of 0.5 the area ratio may be increased to 0.5 without greater error.

Turbulence has subsided at station 4. This statement has reference to large-scale motions not parallel to the direction of net flow. Actually, any undirected turbulence appears as an increase in entropy and is felt throughout the rest of the cycle.

Duct exit (4 to 5):

Air accelerates isentropically with no significant friction or heat transfer.

Case 2 - With Blower

When a blower is used, an extra station (just before the blower) is necessary between the free stream and the heat exchanger.

In front of blower (0 to B):

Compression is adiabatic and isentropic. As these stations are in front of the duct, there is little chance of friction or breakaway.

Blower-diffuser section (B to 1):

Static-pressure rise across the blower-diffuser section is defined. It makes no difference whether static or total pressure is used, inasmuch as blower power is calculated from the total-energy rise across the blower.

No heat transfer occurs. Temperature rise due to compression is so small and rate of heat loss so low that with the flow rates used the temperature change due to heat transfer is quite insignificant.

Entropy rise accounts for any turbulence at station 1. This turbulence will not be excessive if a well-designed blower is used with countervanes.

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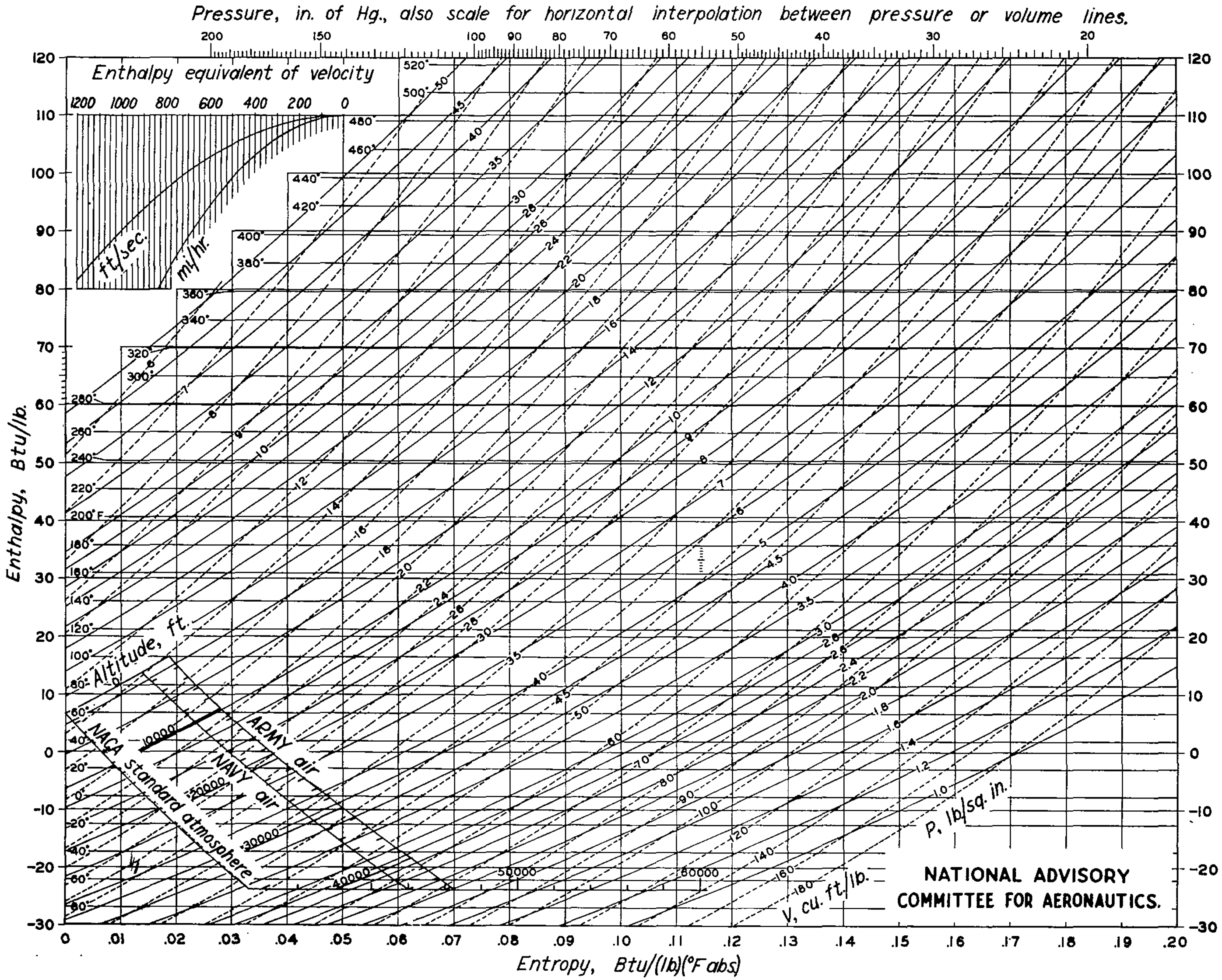

FIGURE 28.- THERMODYNAMIC PROPERTIES OF AIR (APPROX. ONE-THIRD SIZE).